Physics at the Tevatron

Lecture I

Beate Heinemann

University of California, Berkeley

Lawrence Berkeley National Laboratory

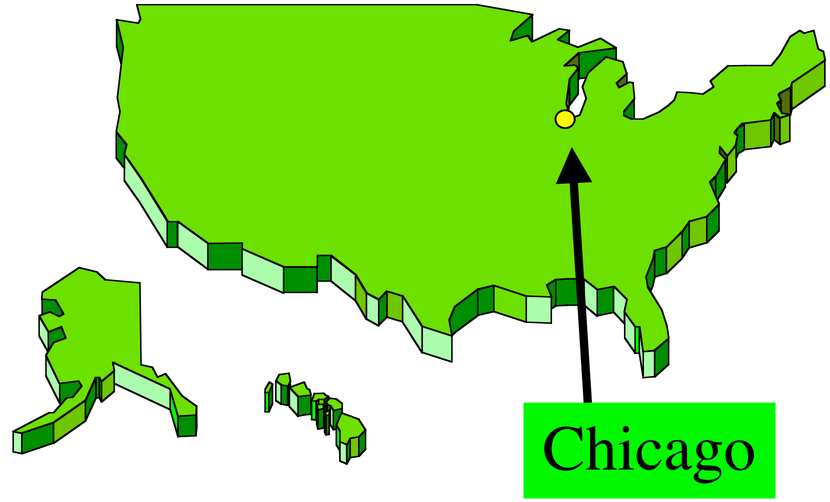
CERN, November 2007

Outline

- Lecture I
  - The Tevatron, CDF and DØ
  - Production Cross Section Measurements
    - Lepton identification
- Lecture II
  - The W boson mass, the Top Quark and the Higgs Boson
    - Lepton calibration, jet energy scale and b-tagging
- Lecture III
  - b hadron lifetimes, B_s mixing and $B_s \rightarrow \mu\mu$ rare decay
    - Vertex resolution and particle identification
- Lecture IV
  - Supersymmetry and High Mass Dilepton/Diphoton
    - Missing E_T

The Tevatron

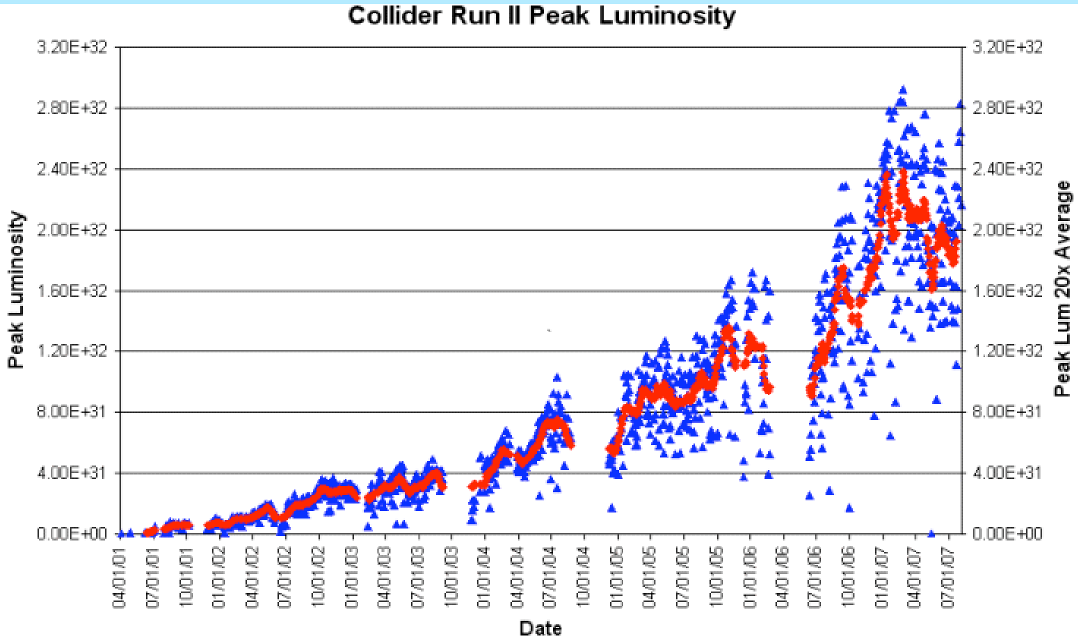
- $p\bar{p}$ collider:
  - 6.5 km circumference
  - Beam energy: 980 GeV
    - $\sqrt{s}$=1.96 TeV
  - 36 bunches:
    - Time between bunches: Δt=396 ns
- Main challenges:
  - Anti-proton production and storage:
    - Stochastic and electron cooling
  - Irregular failures:
    - Kicker prefires, Quenches
- CDF and DØ experiments:
  - 700 physicists/experiment

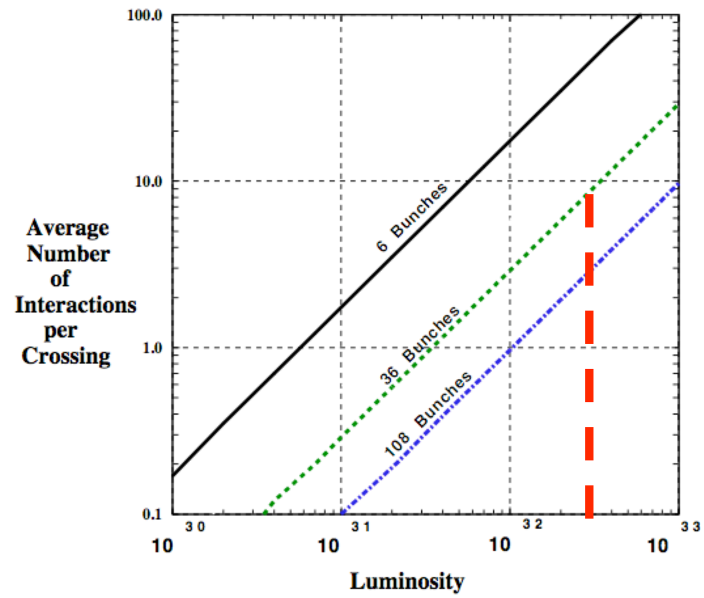


Tevatron Luminosity

Congratulations Fermilab!

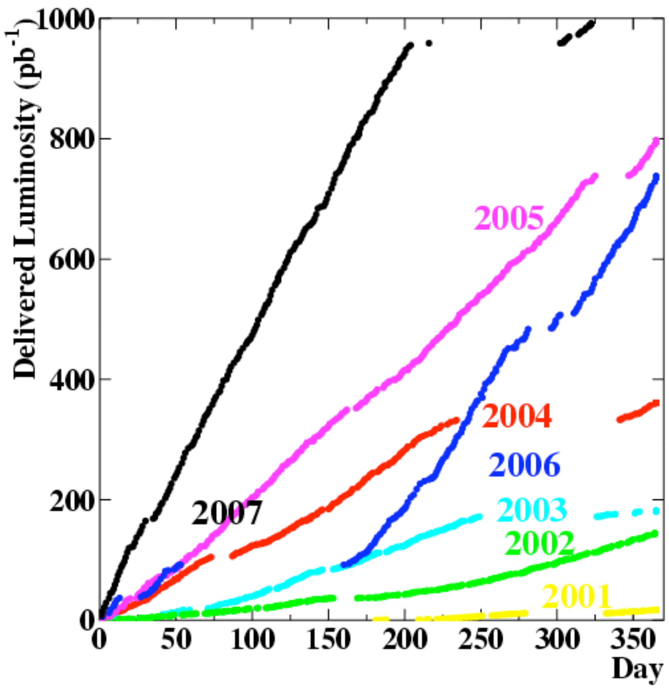
Fermilab has set a world record for peak luminosity of a hadron collider! Operations established store 4431 at 9:11 a.m. yesterday, October 4, with an initial luminosity, or brightness, of 141E30 $cm^{-2}sec^{-1}$. This record exceeds the previous Tevatron record by almost 8 percent, and it exceeds the world record for peak luminosity of a hadron collider achieved 23 years ago by the ISR proton-proton collider at CERN. The ISR achieved a peak luminosity of 140E30 $cm^{-2}sec^{-1}$ at a collision energy of 62 GeV. The Tevatron produces collisions between protons and antiprotons at a collision energy of 1960 GeV. The peak luminosity of the Tevatron has greatly increased since Fermilab began Run II in March 2001, and Fermilab expects to improve the Tevatron peak luminosity even further.

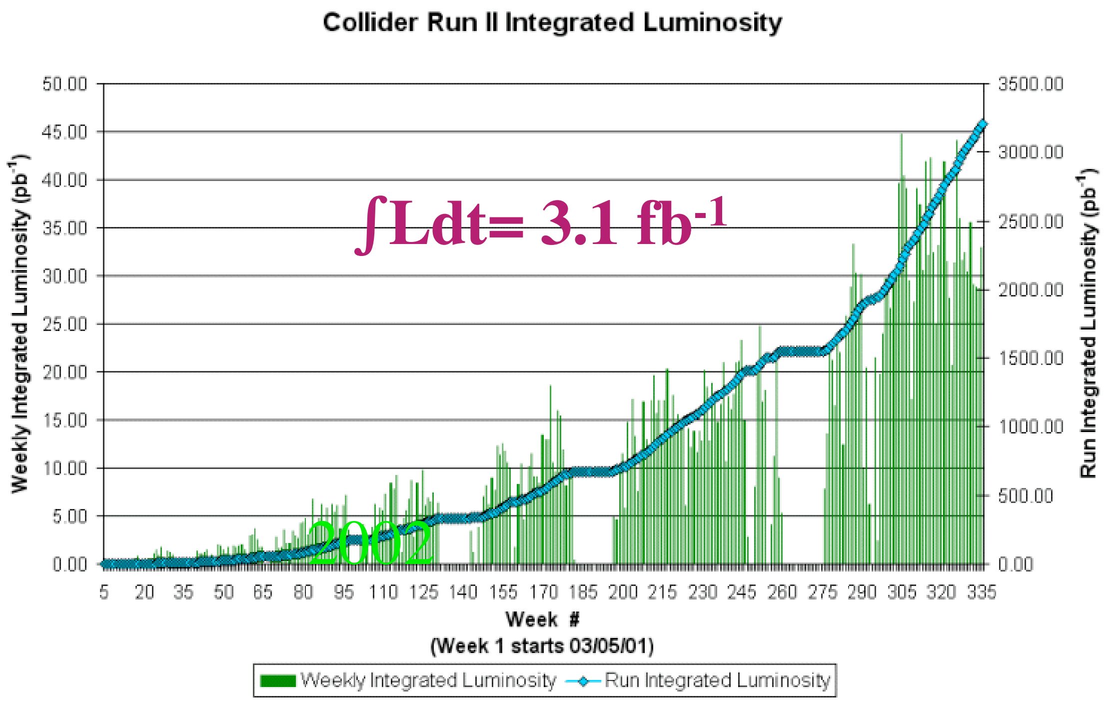




- peak luminosity of 2.8×10^{32} cm^{-2} s^{-1} corresponds to 10 interactions per crossing

Tevatron Performance

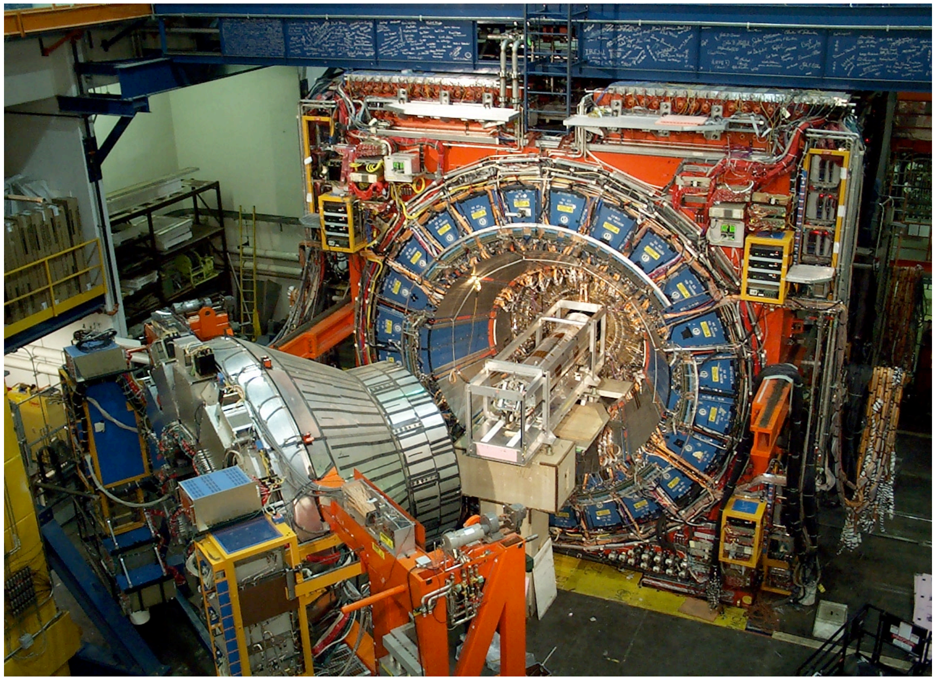


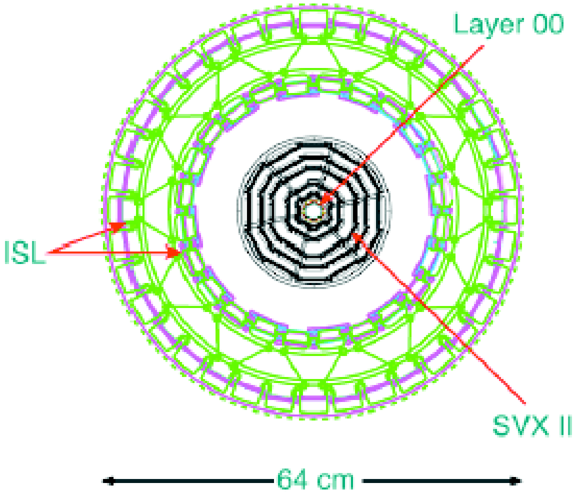


- Integrated luminosity more than 3 fb^{-1} by now
  - First years were difficult
    - March'01-March'02 used for commissioning of detectors
    - Physics started in March'02
  - Luminosity doubles every year
    - Typically 150 pb^{-1} per month in 2007
- Just coming out of 2-month shutdown

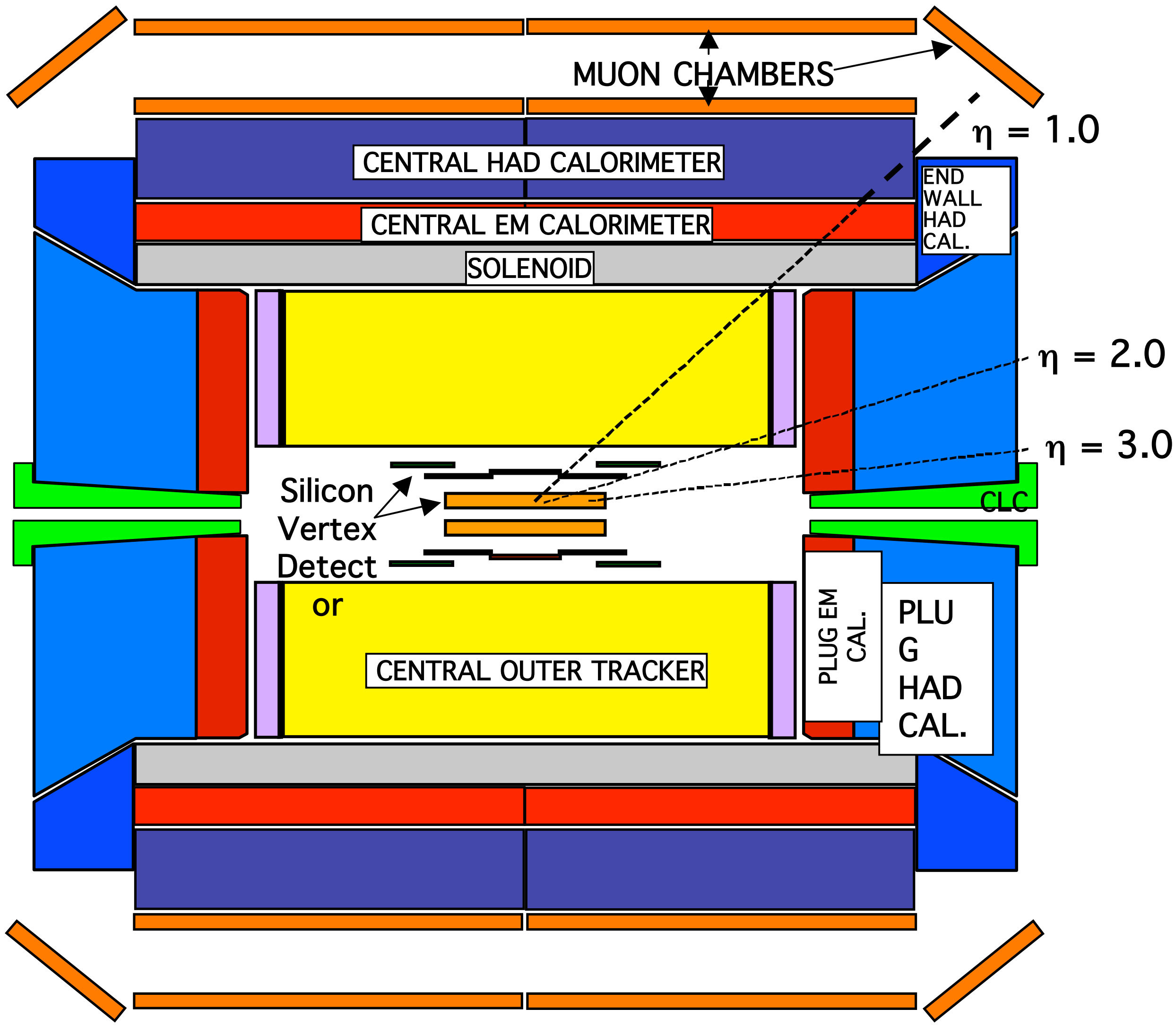
CDF

- Core detector operates since 1985:
  - Central Calorimeters
  - Central muon chambers
- Major upgrades for Run II:
  - Drift chamber: COT
  - Silicon: SVX, ISL, L00
    - 8 layers
    - 700k readout channels
    - 6 m^2
    - material:15% X_0
  - Forward calorimeters
  - Forward muon system
    - Improved central too
  - Time-of-flight
  - Preshower detector
  - Timing in EM calorimeter
  - Trigger and DAQ



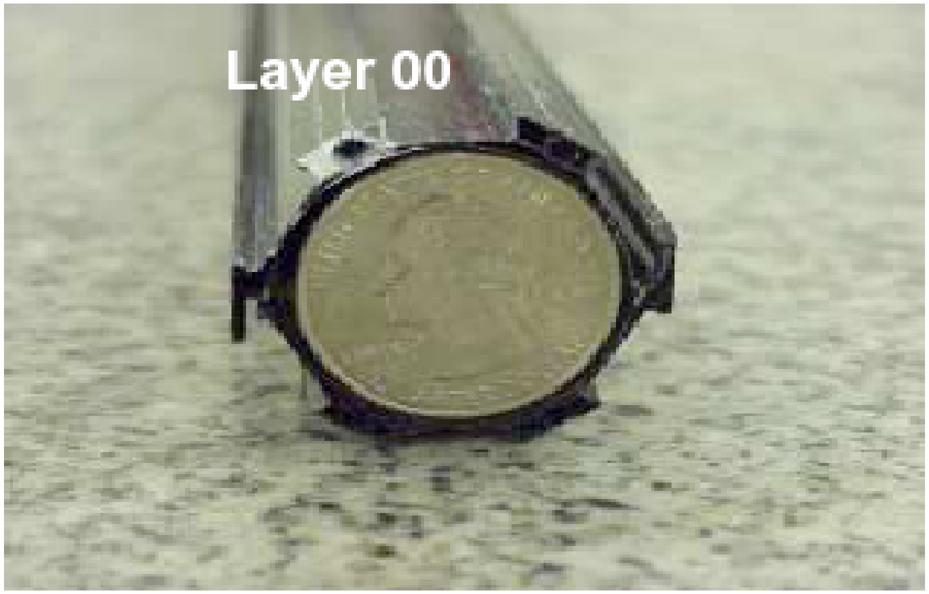


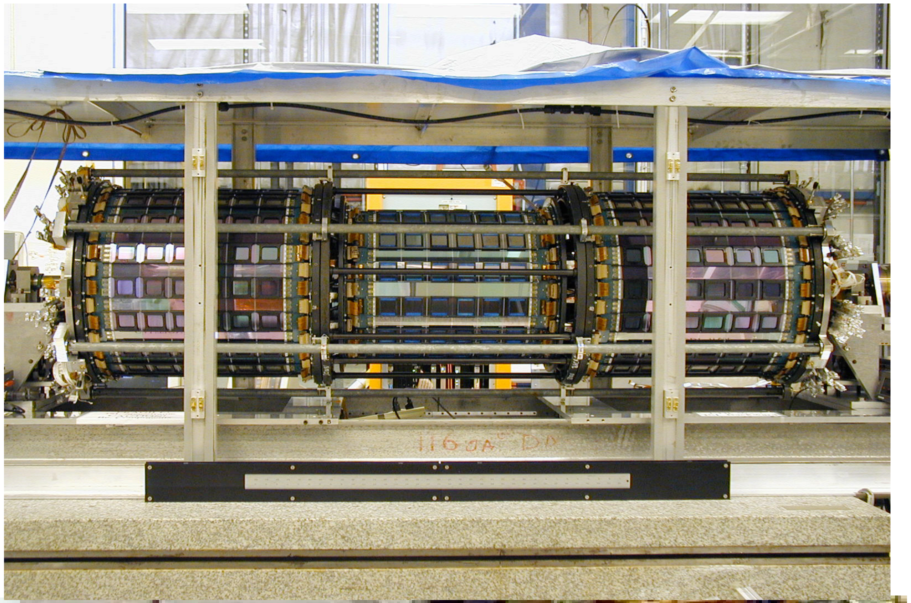
CDF

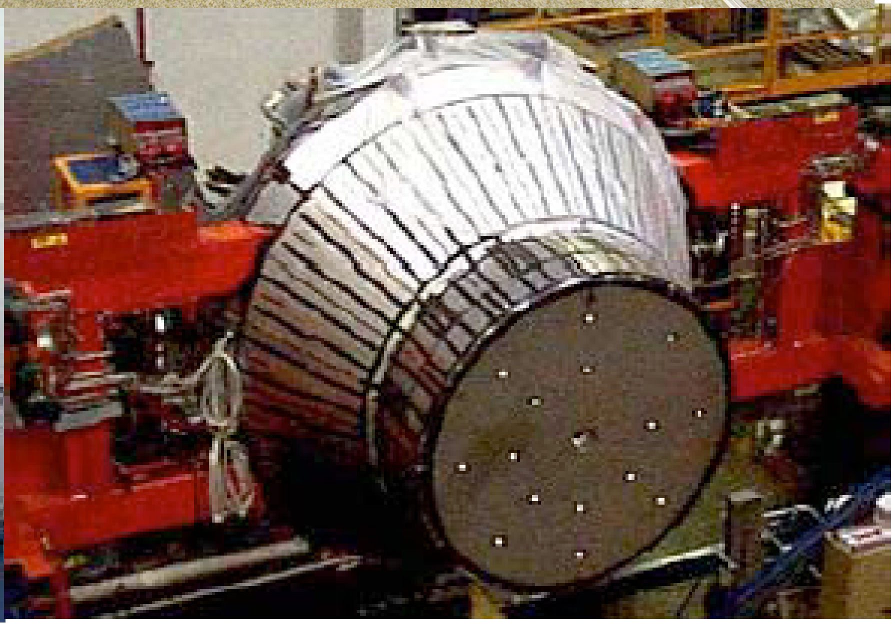


MUON CHAMBERS
η = 1.0
CENTRAL HAD CALORIMETER
END
WALL
HAD
CAL.
CENTRAL EM CALORIMETER
SOLENOID
η = 2.0
η = 3.0
Silicon
Vertex
Detect
or
CLC
PLUG EM
CAL.
PLU
G
HAD
CAL.
CENTRAL OUTER TRACKER

Some new CDF Subdetectors



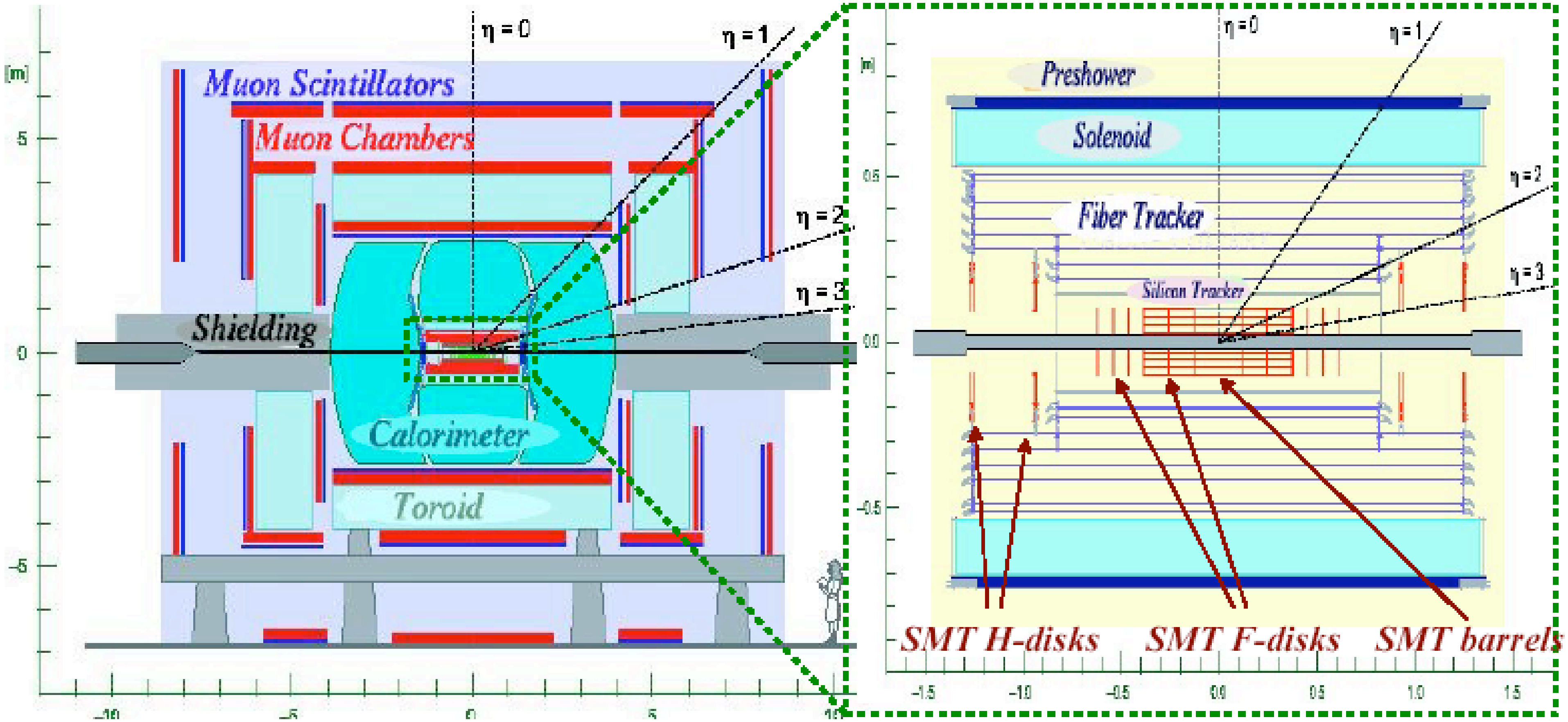




DØ Detector

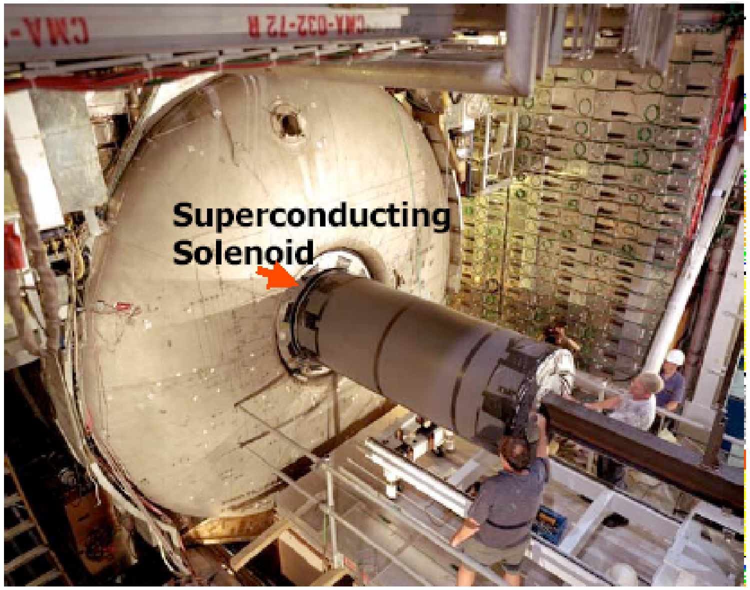
- Retained from Run I
  - Excellent muon coverage
  - Compact high granularity LAr calorimeter
- New for run 2:
  - 2 Tesla magnet !
  - Silicon detector
  - Fiber tracker
  - Trigger
  - Readout
  - Forward roman pots

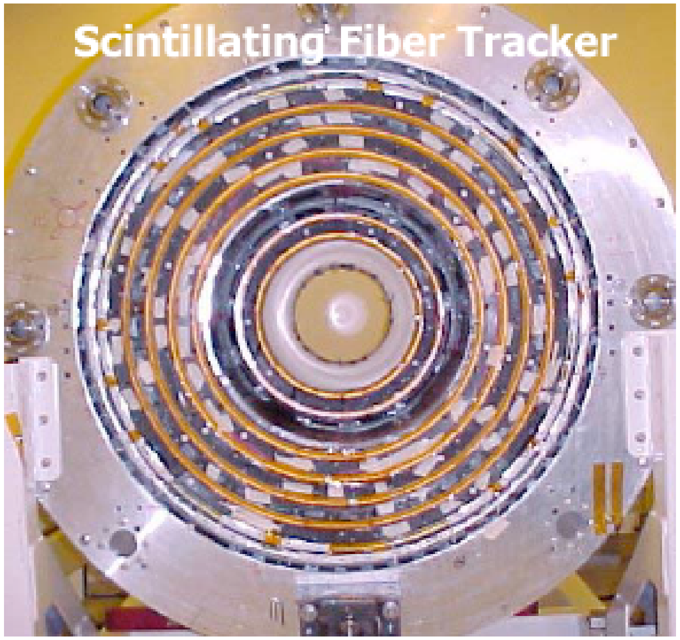
DØ Detector

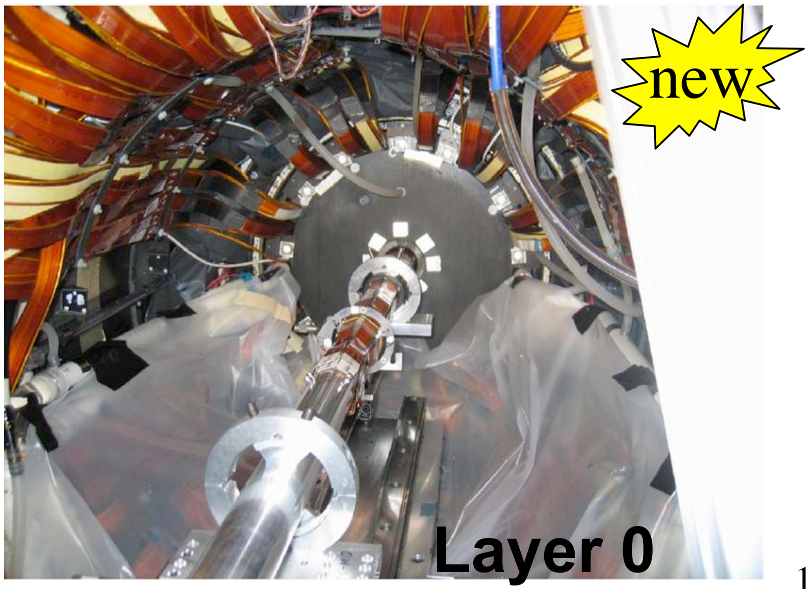


η = 0
η = 1
η = 2
η = 3
[m]
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid
Preshower
Solenoid
Fiber Tracker
Silicon Tracker
SMT H-disks
SMT F-disks
SMT barrels

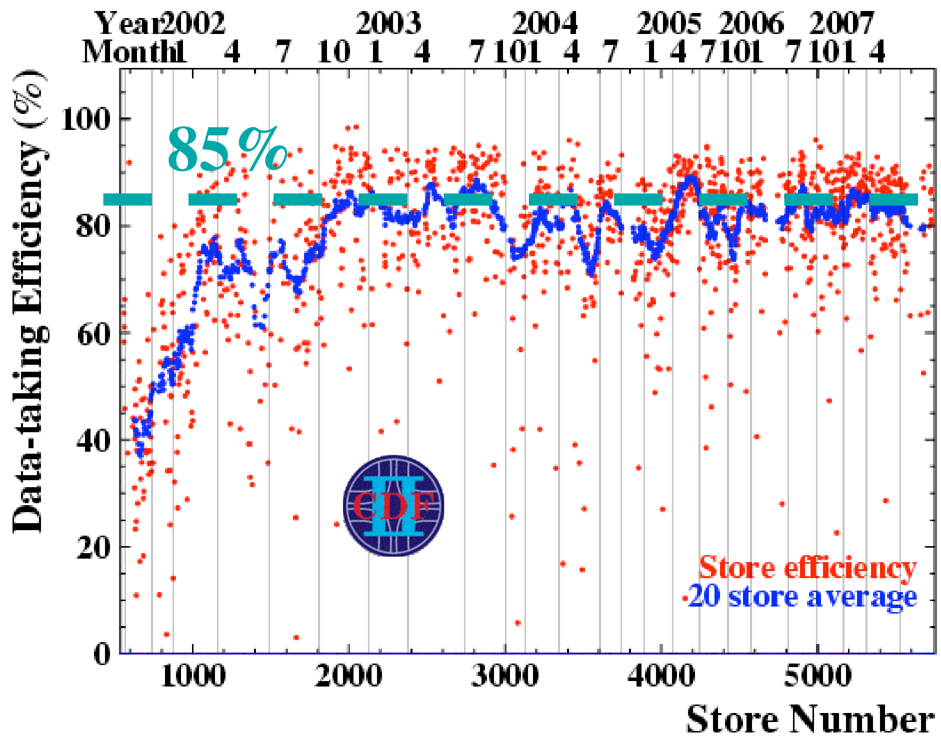
Pictures of DØ Subdetectors

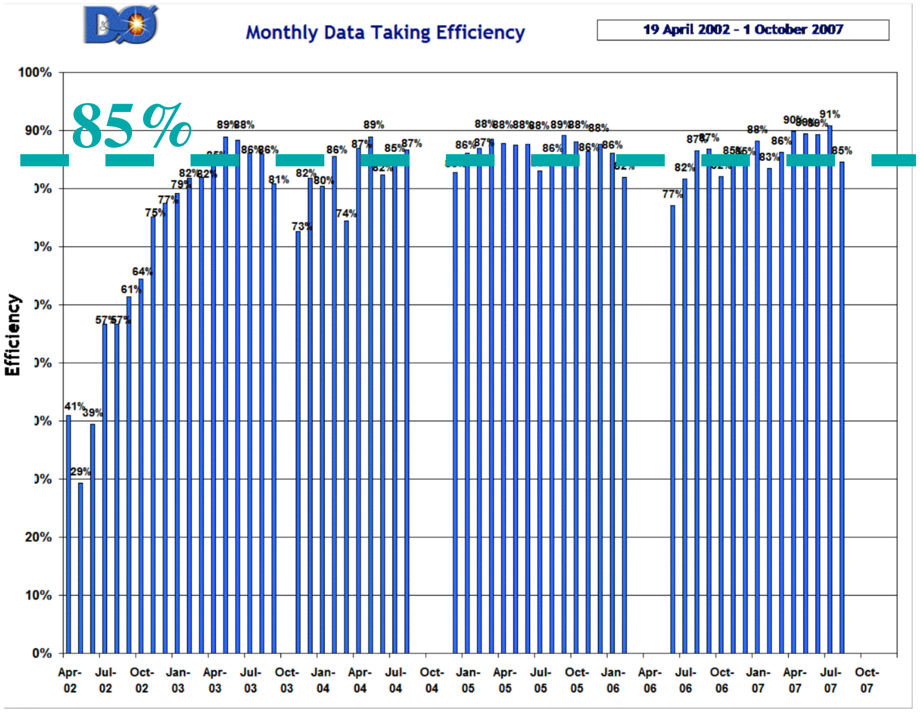






Detector Operation





- Data taking efficiency about 85%
- All components working very well:
  - 93% of Silicon detector operates, 82-96% working well
  - Expected to last up to 8 fb^{-1}

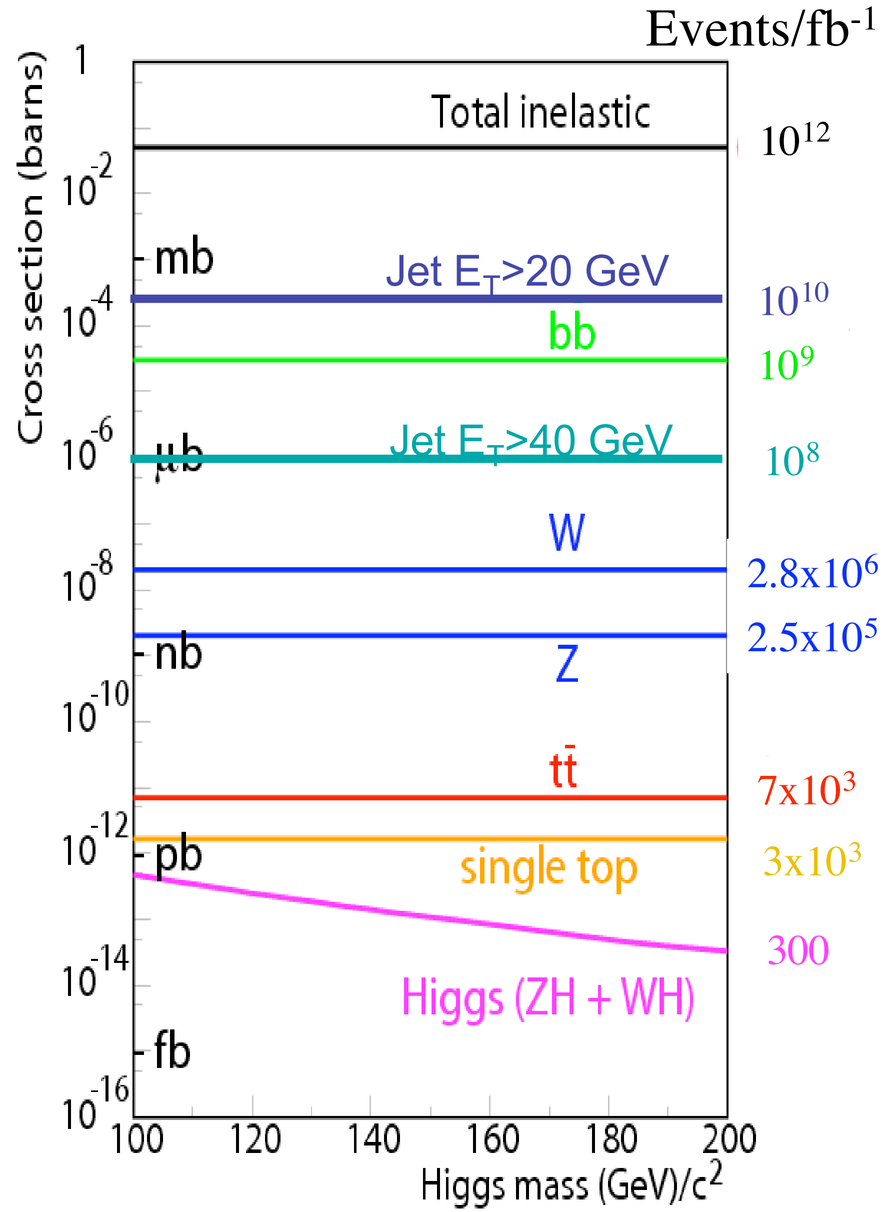
Detector Performances

	CDF	DØ
$\sigma_M(J/\psi \rightarrow \mu^+\mu^-)$	12 MeV	60 MeV
$\sigma_M(Z \rightarrow \mu^+\mu^-)$	2.5 GeV	6 GeV
$\sigma_M(Z \rightarrow e^+e^-)$	2.8-3.2 GeV	3.1 GeV
$\sigma(E_t^{jet})/ E_t^{jet}$	~16%	~14%
δd_0	~30 μm	~30 μm

- **Good resolution for**
  - track momenta
  - calorimeter energies
  - vertex

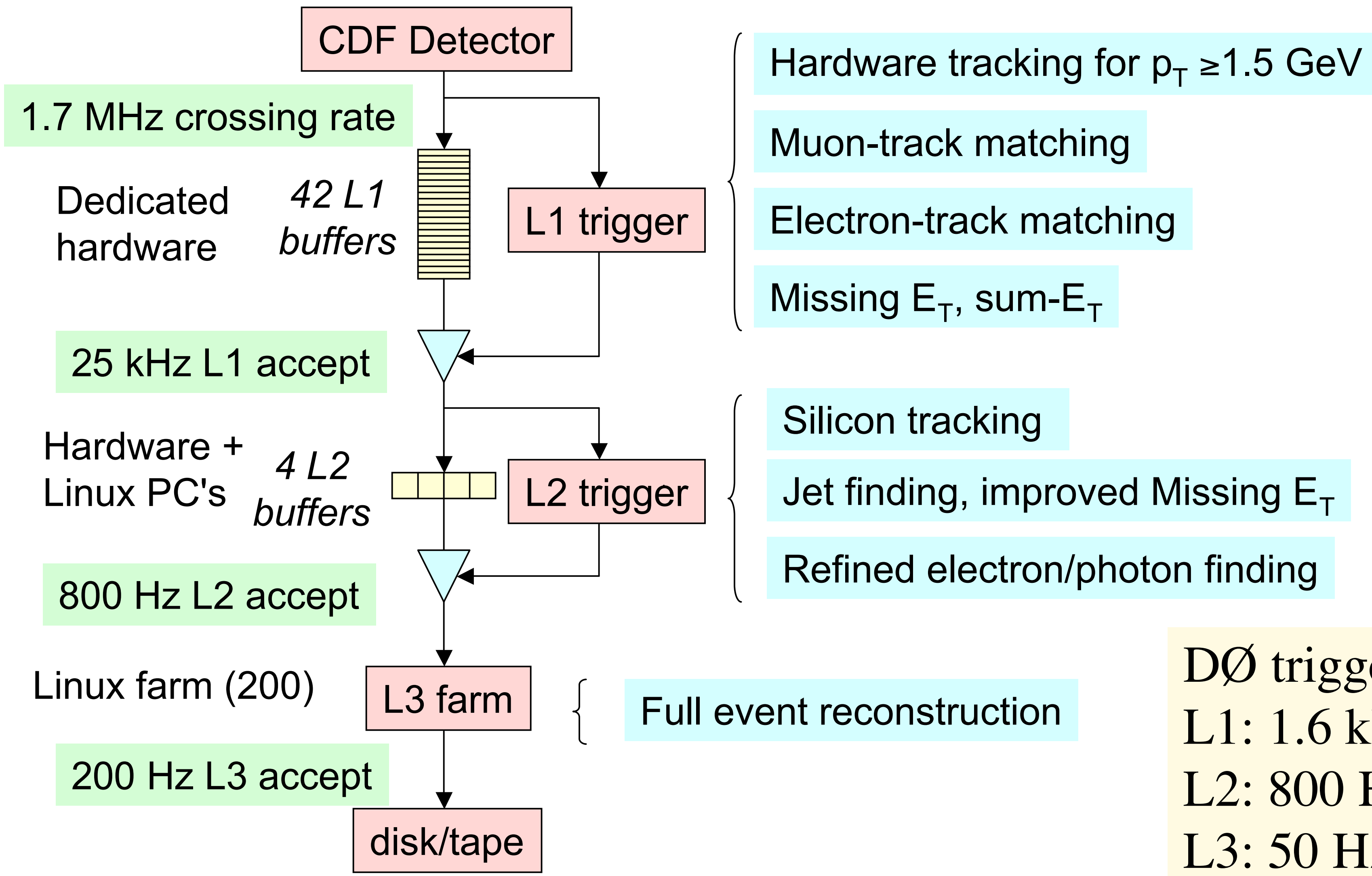
Processes and Cross Sections

- Cross section:
  - Total inelastic cross section is huge
    - Used to measure luminosity
- Rates at e.g. $L=1\times10^{32}\ cm^{-2}s^{-1}$:
  - Total inelastic: 70 MHz
  - bb: 42 kHz
  - Jets with E_T>40 GeV: 300 Hz
  - W: 3 Hz
  - Top: 25/hour
- Trigger needs to select the interesting events
  - Mostly fighting generic jets!



Triggering at hadron colliders

The trigger is the key at hadron colliders



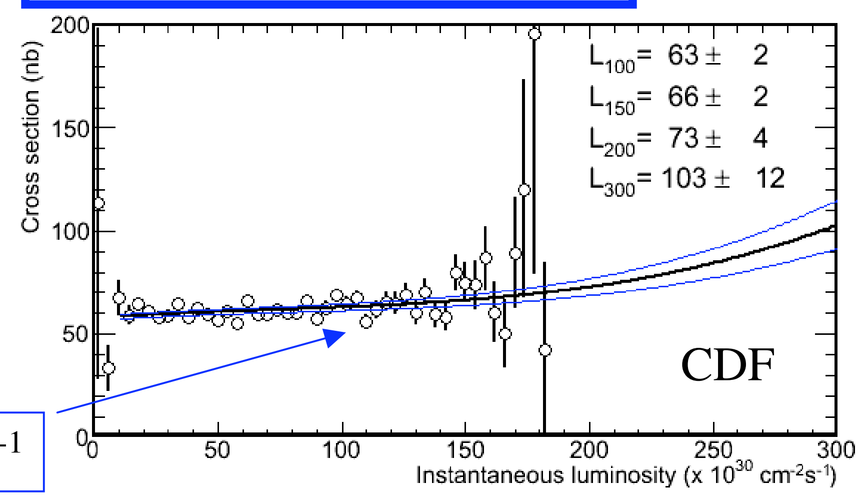
DØ trigger:
L1: 1.6 kHz
L2: 800 Hz
L3: 50 Hz

Typical Triggers and their Usage

- Unprescaled triggers for primary physics goals
- Examples:
  - Inclusive electrons, muons p_T>20 GeV:
    - W, Z, top, WH, single top, SUSY, Z',Z'
  - Dileptons, p_T>4 GeV:
    - SUSY
  - Lepton+tau, p_T>8 GeV:
    - MSSM Higgs, SUSY, Z
    - Also have tau+MET: W->taunu
  - Jets, E_T>100 GeV
    - Jet cross section, Monojet search
    - Lepton and b-jet fake rates
  - Photons, E_T>25 GeV:
    - Photon cross sections, Jet energy scale
    - Searches (GMSB SUSY)
  - Missing E_T>45 GeV
    - SUSY
    - ZH->vvbb

- Prescale triggers because:
  - Not possible to keep at highest luminosity
  - Needed for monitoring
  - Prescales depend often on Lumi
- Examples:
  - Jets at E_T>20, 50, 70 GeV
  - Inclusive leptons >8 GeV
  - B-physics triggers
  - Backup triggers for any threshold, e.g. Met, jet ET, etc…
    - At all trigger levels

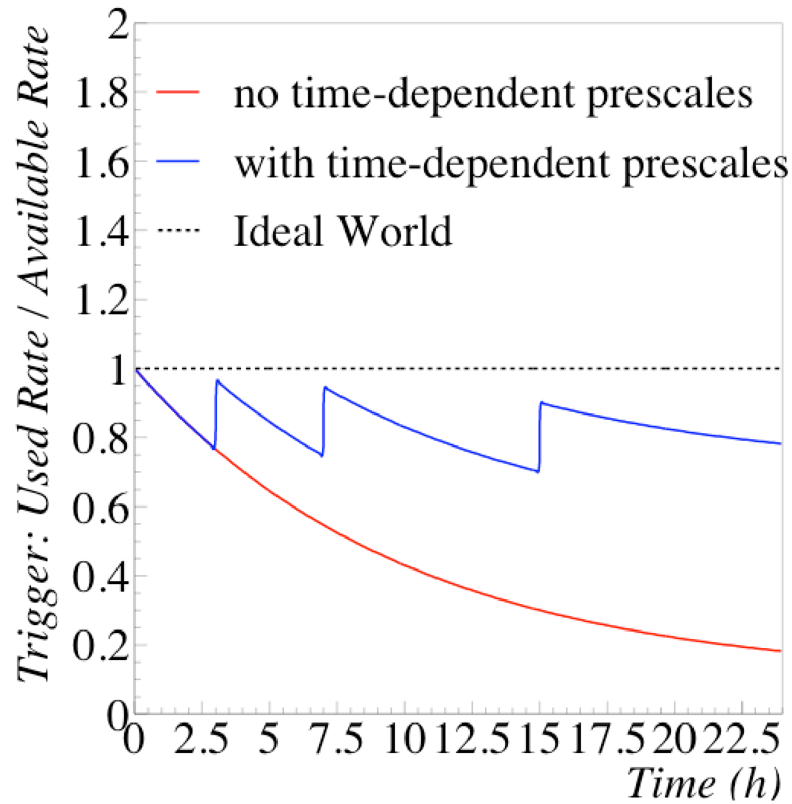
single electron trigger



Rate= 6 Hz at L=100x10^{30} cm^{-2}s^{-1}

Trigger Operation

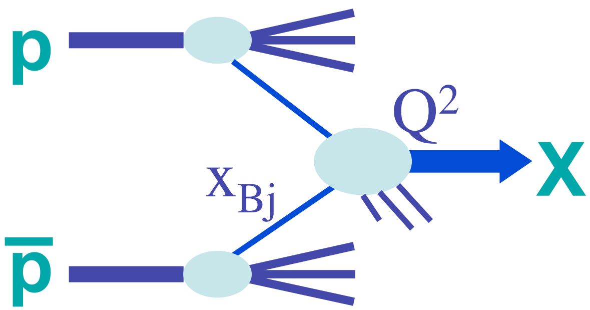
- Aim to maximize physics at trigger level:
  - Trigger cross section:
    - Nevent/nb^{-1}
    - Independent of Luminosity
  - Trigger Rate:
    - Cross Section x Luminosity
- Luminosity falls within store
  - Rate also falls within store
  - 75% of data are taken at <2/3 of peak luminosity
- Use sophisticated prescale system to optimize bandwidth usage
  - Trigger more physics!

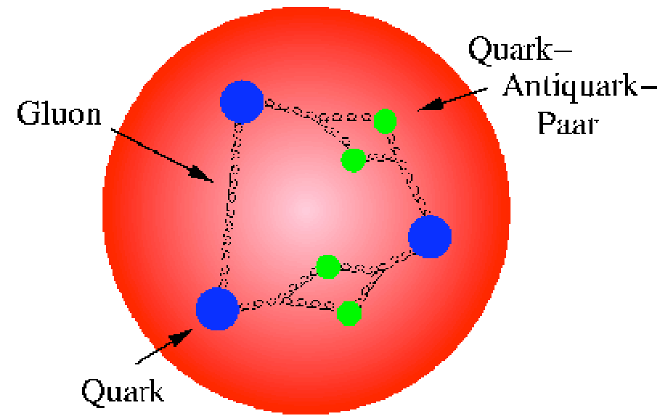


	CDF	DØ
L1 bits	64	128
L2 bits	125	>128
L3 bits	173	418

The Proton

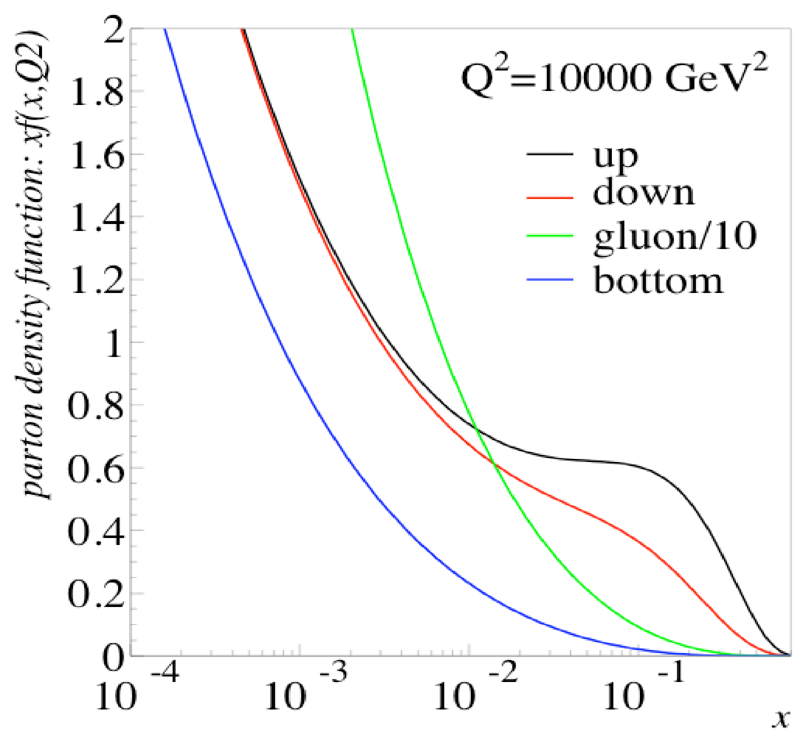
- It's complicated:
  - Valence quarks
  - Gluons
  - Sea quarks



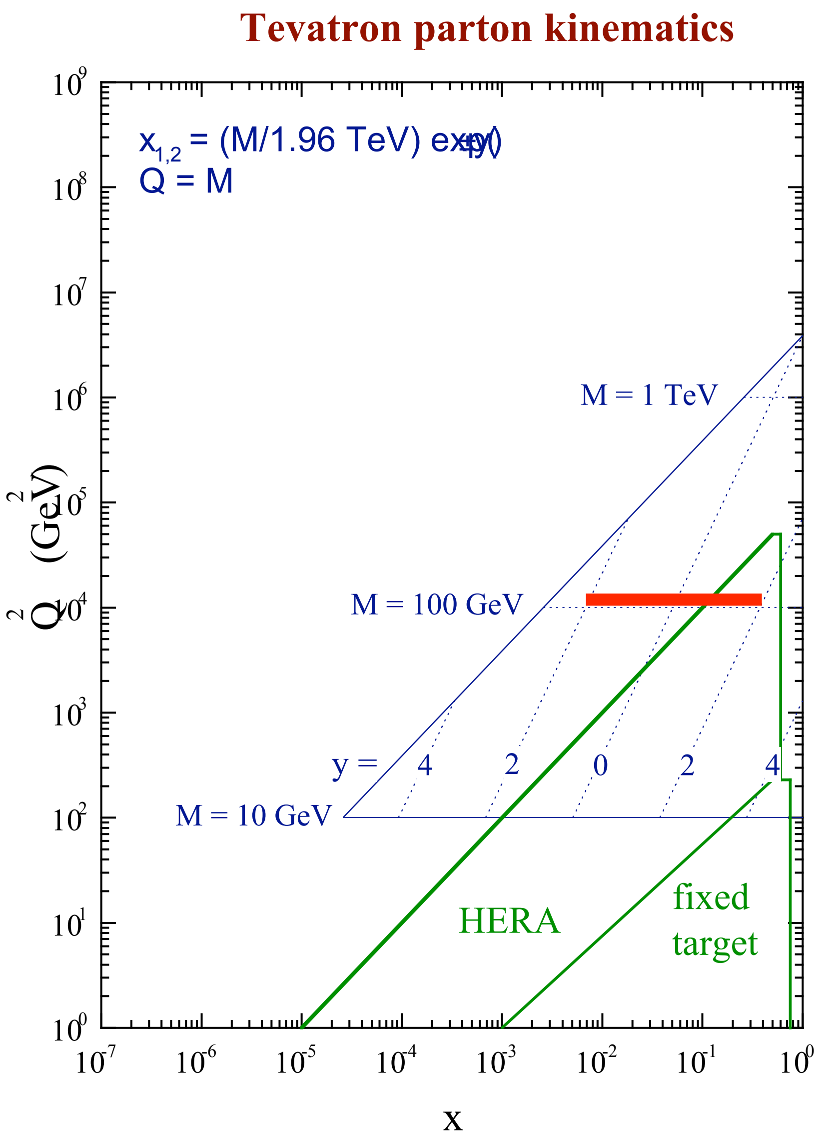


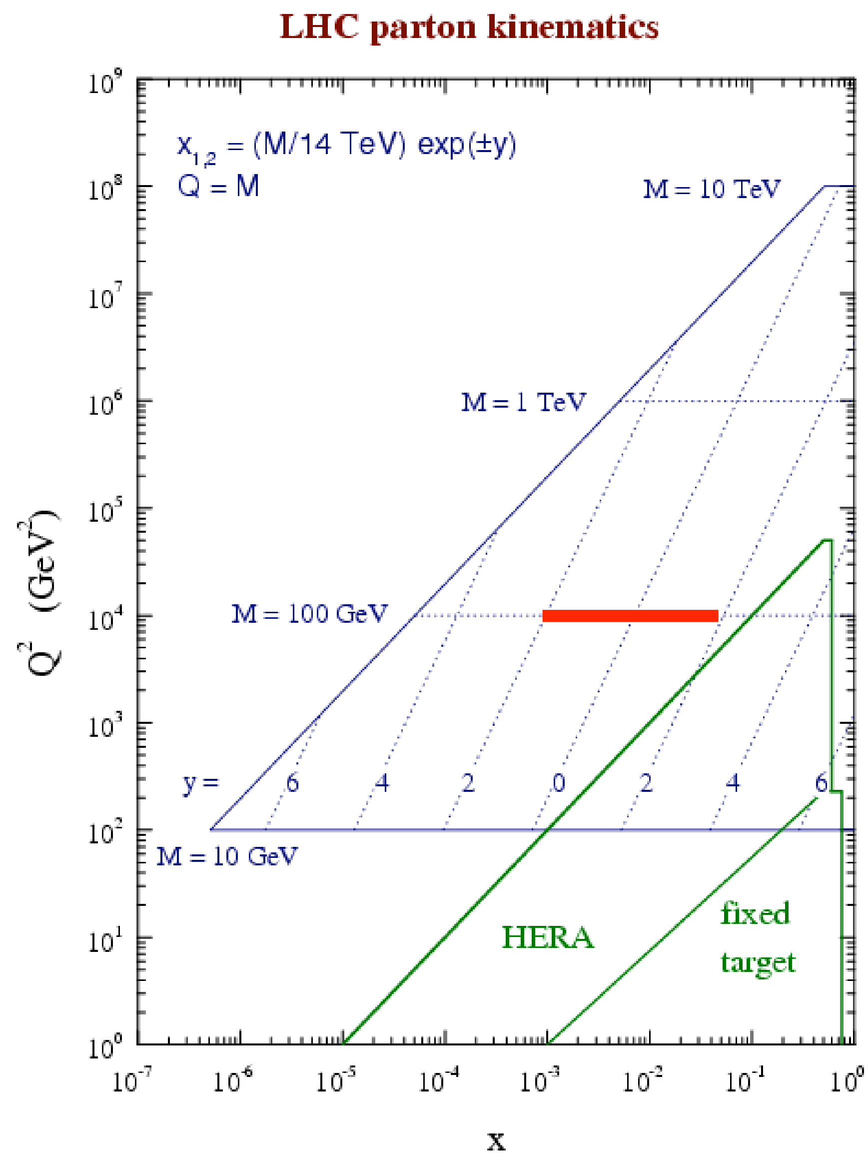
- Exact mixture depends on:
  - Q^2: ~$(M^2+p_T^2)$
  - x_{Bj}: fractional momentum carried by parton
- Hard scatter process:

$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$



Parton Kinematics

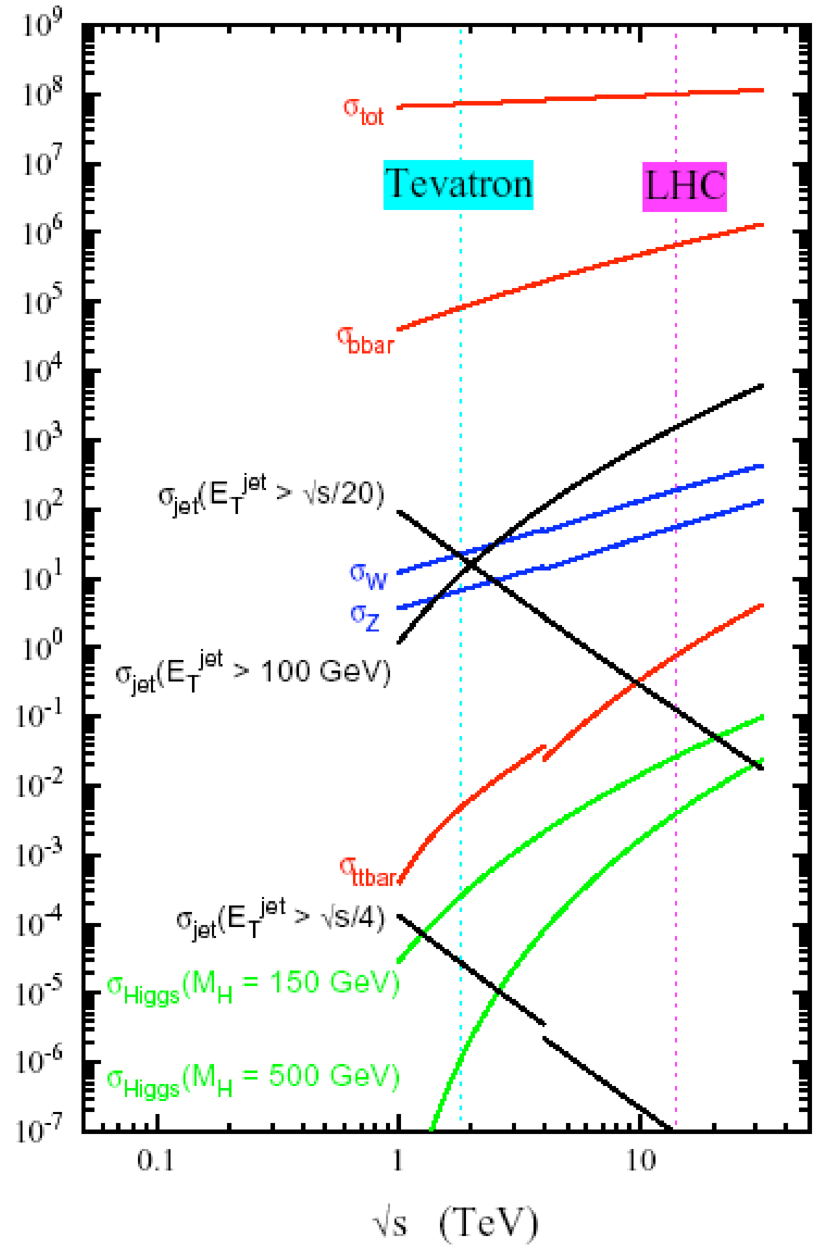




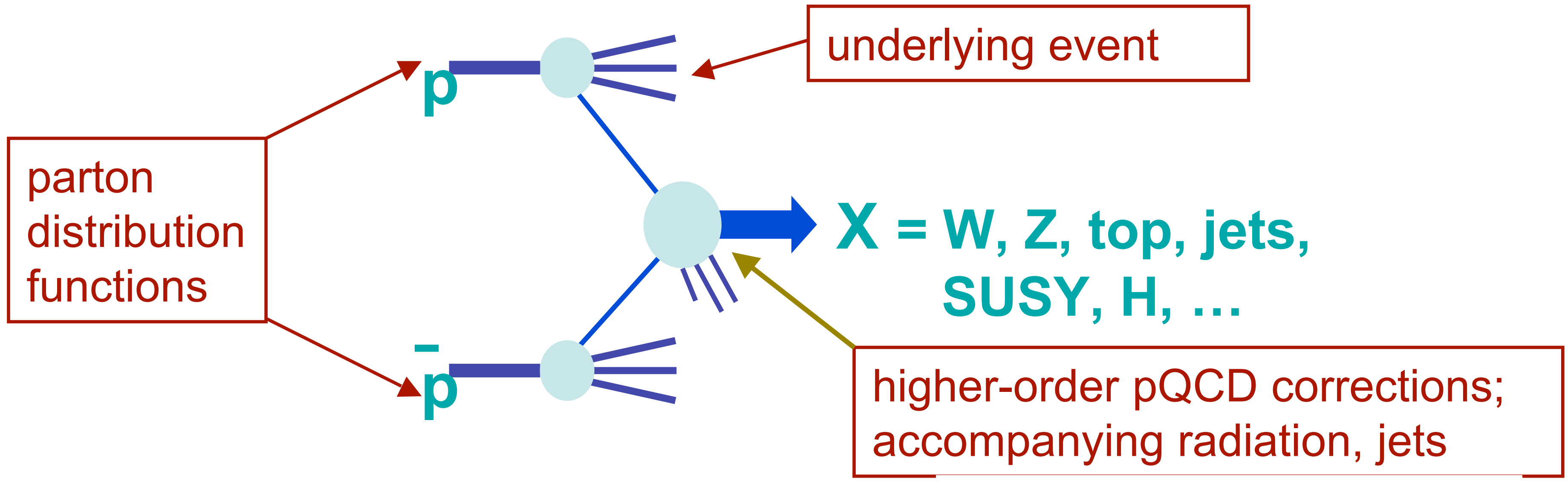
- For M=100 GeV: probe 10 times higher x at Tevatron than LHC

Tevatron vs LHC

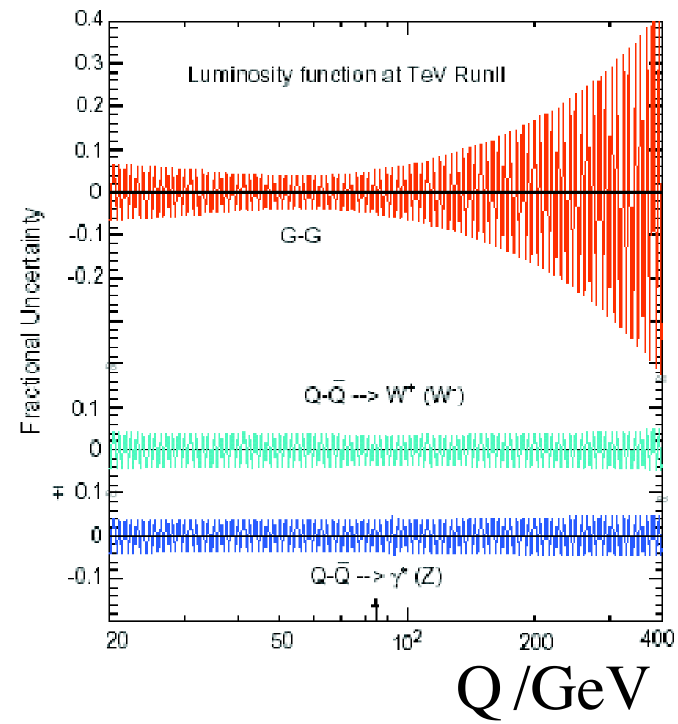
- Compare to LHC
  - Cross sections of heavy objects rise much faster, e.g.
    - top cross section
    - Jet cross section E_T>100 GeV
- Relative importance of processes changes
  - Jet background to W's and Z's
  - W background to top
  - backgrounds to Higgs



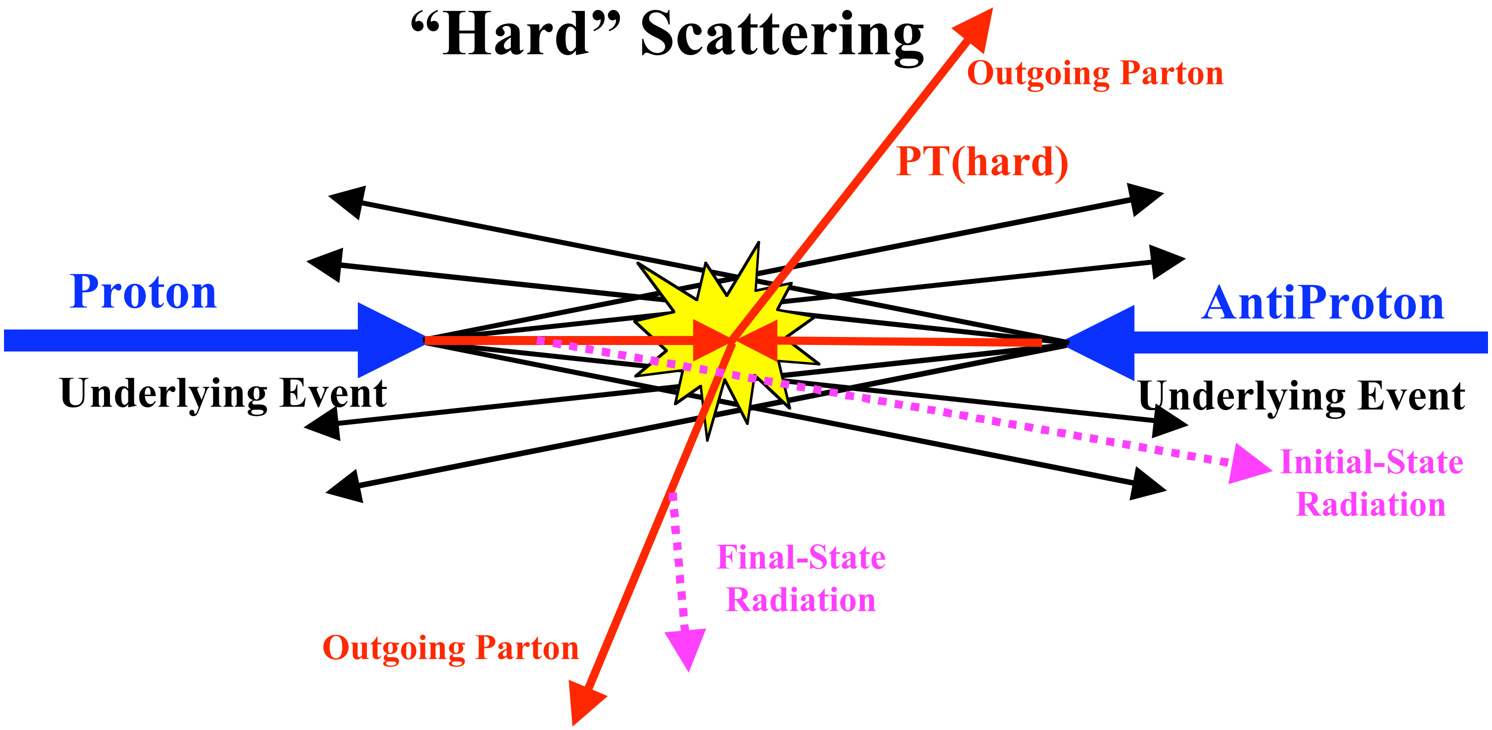
The Proton is Messy



- We don't know
  - Which partons hit each other
  - What their momentum is
  - What the other partons do
- We know roughly (2-30%)
  - The parton content of the proton
  - The cross sections of processes



Every Event is Complicated



- "Underlying event":
  - Initial state radiation
  - Interactions of other partons in proton
- Many forward particles escape detection
  - Transverse momentum ~0
  - Longitudinal momentum >>0

Kinematic Constraints and Variables

- Transverse momentum, p_T
  - Particles that escape detection ($\theta<3^o$) have $p_T \approx 0$
  - Visible transverse momentum conserved $\sum_I p_T^i \approx 0$
    - Very useful variable!
- Longitudinal momentum and energy, p_z and E
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - Not so useful variable
- Angle:
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

For M=0

$$y = \eta = -\ln(\tan \frac{\theta}{2})$$

Standard Model
Processes and Cross Sections

Why Measure Cross Sections?

1. They test QCD calculations
   - They help us to find out content of proton:
     - Gluons, light quarks, c- and b-quarks
   - A cross section that disagrees with theoretical prediction could be first sign of new physics:
     - E.g. quark substructure (highest jet E_T)

Why Measure Cross Sections?

1. They test QCD calculations
   - They help us to find out content of proton:
     - Gluons, light quarks, c- and b-quarks
   - A cross section that disagrees with theoretical prediction could be first sign of new physics:
     - E.g. quark substructure (highest jet E_T)

2. They force us to understand the detector

Why Measure Cross Sections?

1. They test QCD calculations
   – They help us to find out content of proton:
     • Gluons, light quarks, c- and b-quarks
   – A cross section that disagrees with theoretical prediction could be first sign of new physics:
     • E.g. quark substructure (highest jet E_T)

2. They force us to understand the detector

3. Noone believes us anything without us showing we can measure cross sections

Luminosity Measurement

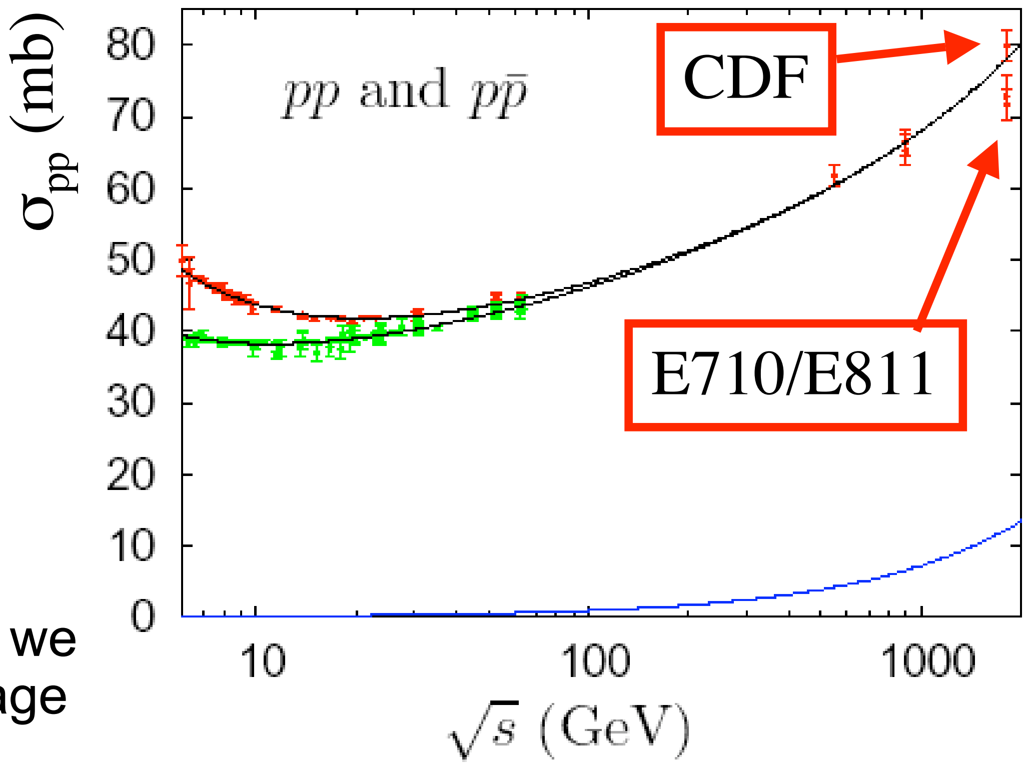
$$R_{pp} = \mu_{pp} \cdot f_{BC} = \sigma_{inel} \cdot \varepsilon_{pp} \cdot \delta(L) \cdot L$$

σ_{LM}

L – luminosity
f_{bc} – Bunch Crossing rate
μ_a – # of pp / BC

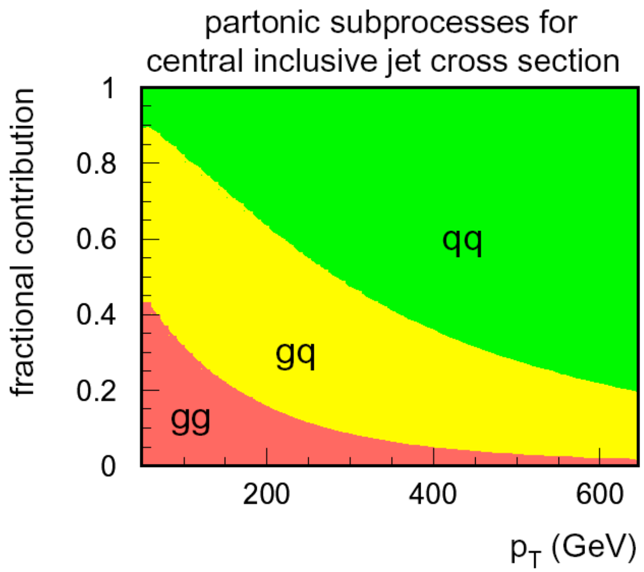
σ_{inel} – inelastic x-section
ε_{pp} – acceptance for a single pp
$\delta(L)$ – detector non-linearity

- Measure events with 0 interactions
  - Related to R_{pp}
- Normalize to measured inelastic pp cross section
  - Measured by CDF and E710/E811
  - Differ by 2.6 sigma
  - For luminosity normalization we use the error weighted average
  - CDF and DØ use the same
  - Unlike in Run 1…

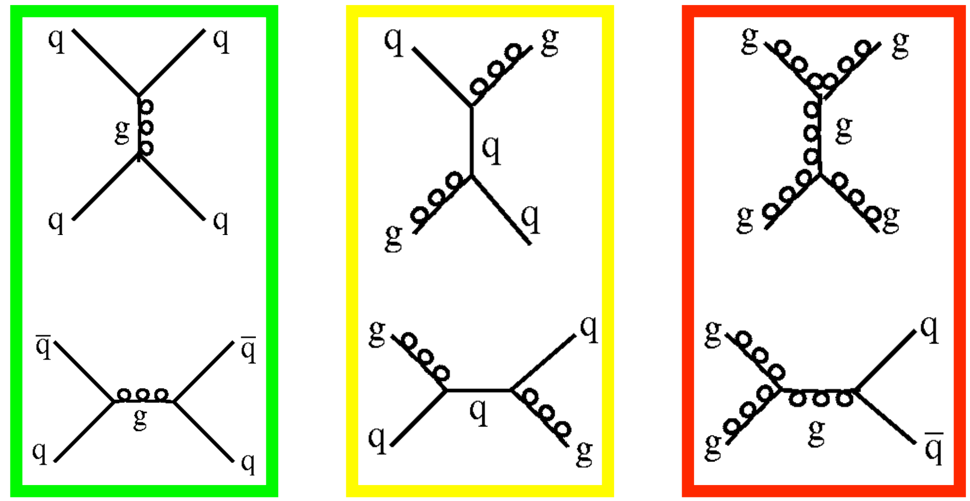


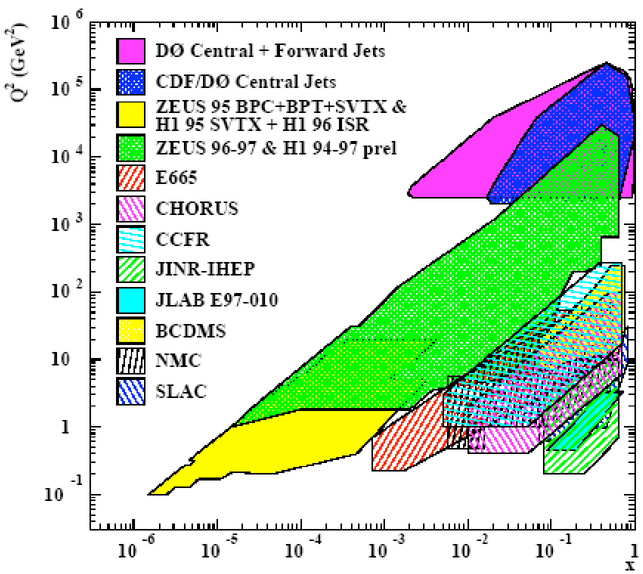
$$\overline{\sigma}_{in} = 60.7 \pm 2.4 mb @ 1.96\,\mathrm{TeV}$$

Jet Cross Sections



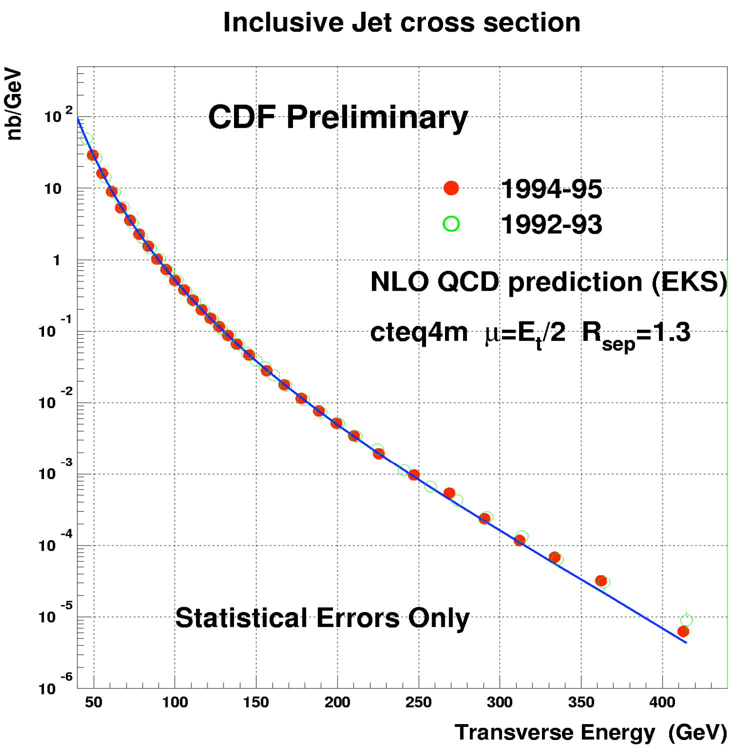
- Inclusive jets: processes qq, qg, gg

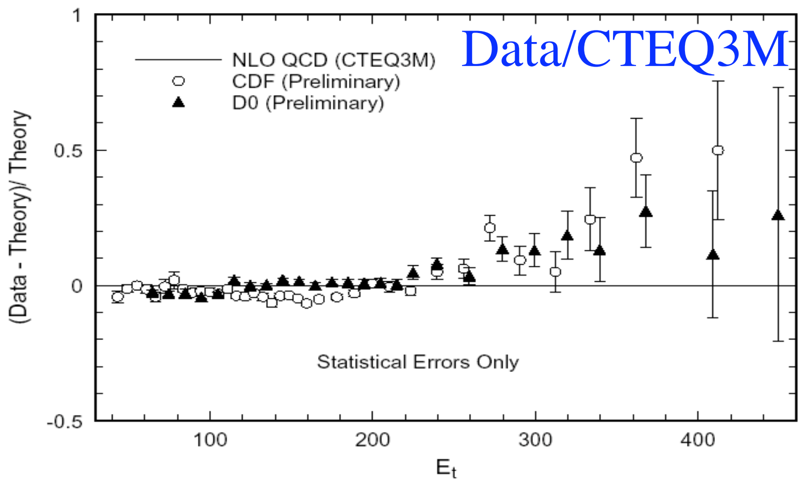




- Measure at highest Q^2 and x
  - Testing new grounds
  - High Q^2
    - new physics at TeV scale?

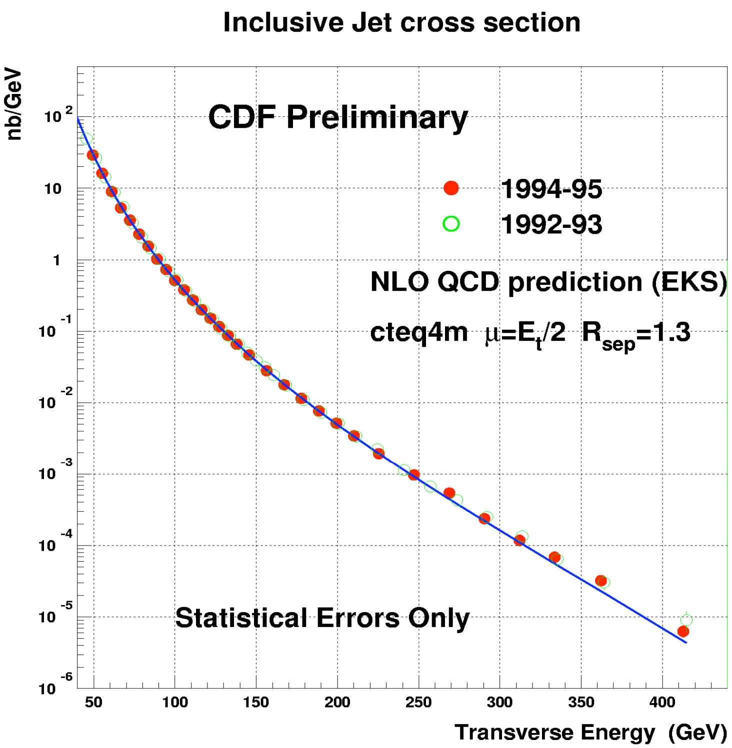
Jet Cross Section History



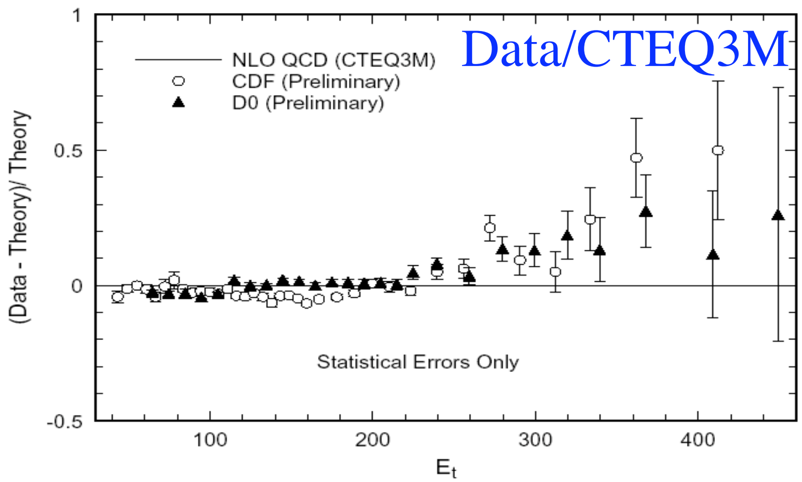


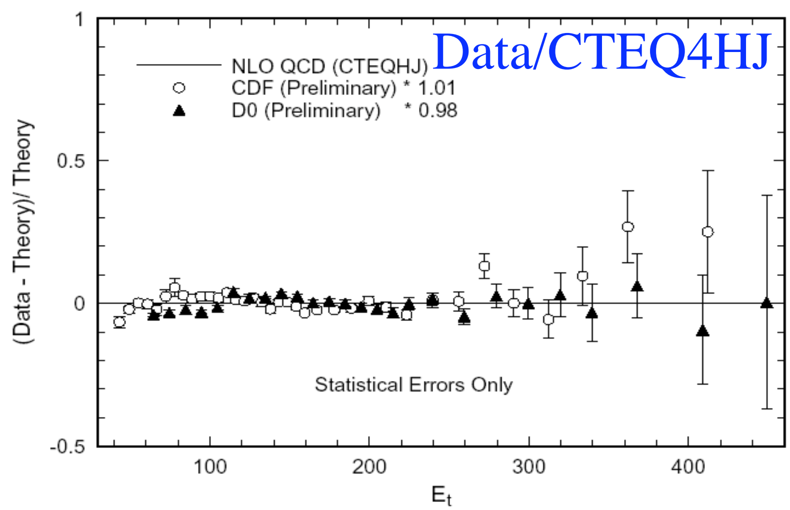
- Run I (1996):
  - Excess at high E_T
  - Could be signal for quark substructure?!?

Jet Cross Section History

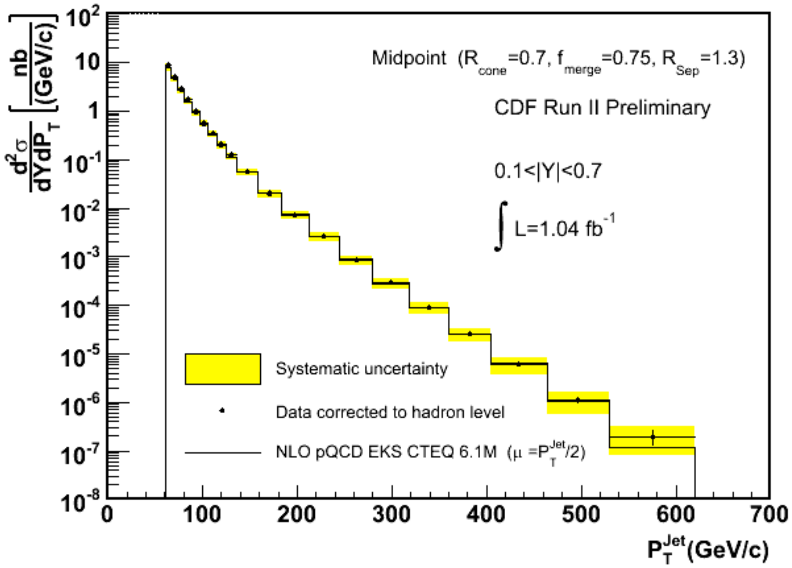


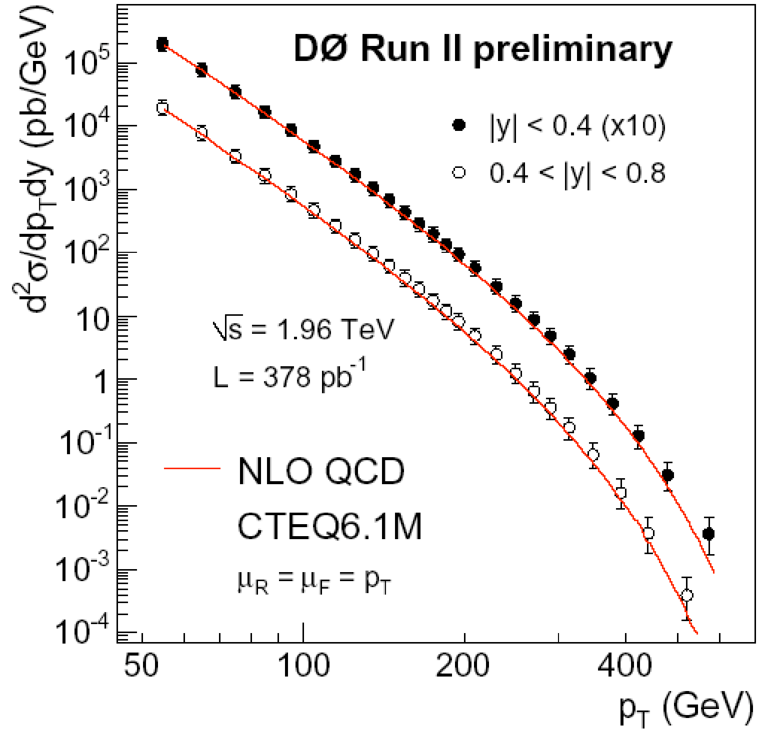
- Since Run I:
  - Revision of parton density functions
    - Gluon is uncertain at high x
  - Different jet algorithms
    - MidPoint
    - k_T

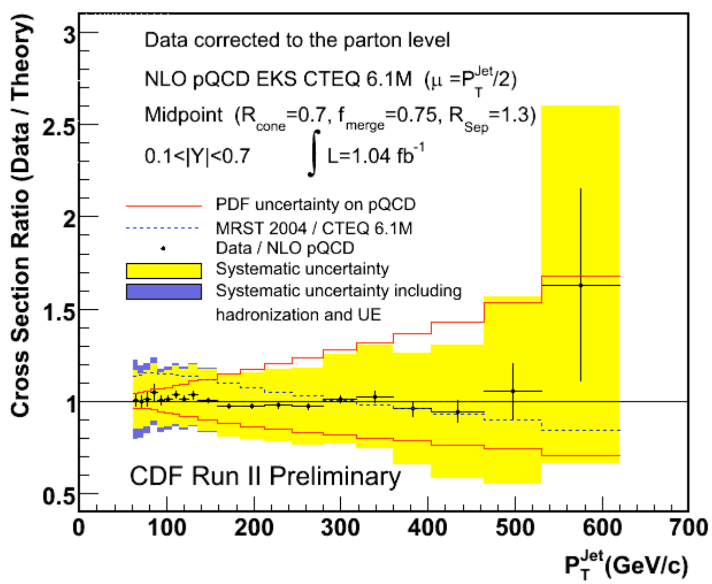




Jet Cross Sections in Run II

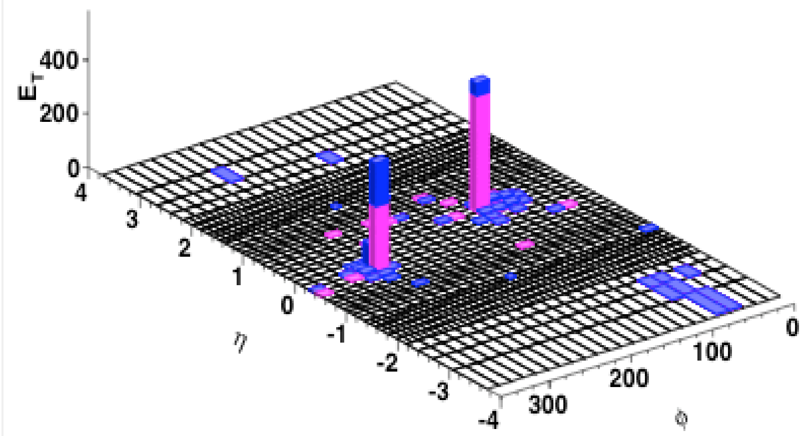






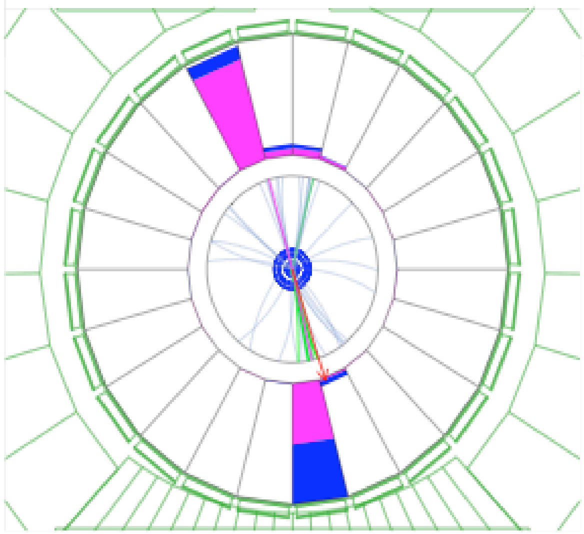
- Excellent agreement with QCD calculation over 8 orders of magnitude!
- No excess any more at high E_T
  - Large pdf uncertainties will be constrained by these data

Highest Mass Dijet Event: M=1.4 TeV



CDF Run II Preliminary

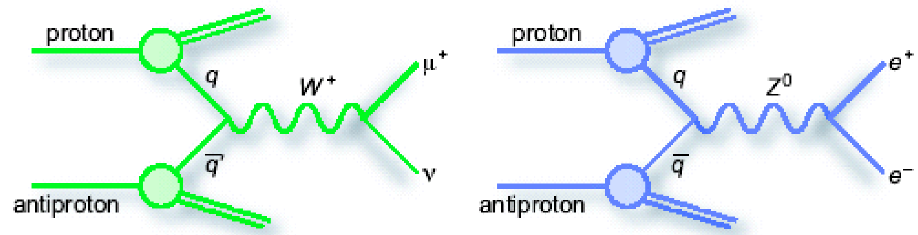
```
Jet Et1 = 666 GeV (corr)
          583 GeV (raw)
eta1    = 0.31 (detector)
          0.43 (corr z)

Jet Et2 = 633 GeV (corr)
          546 GeV (raw)
eta2    = -0.30 (detector)
          -0.19 (corr z)
```

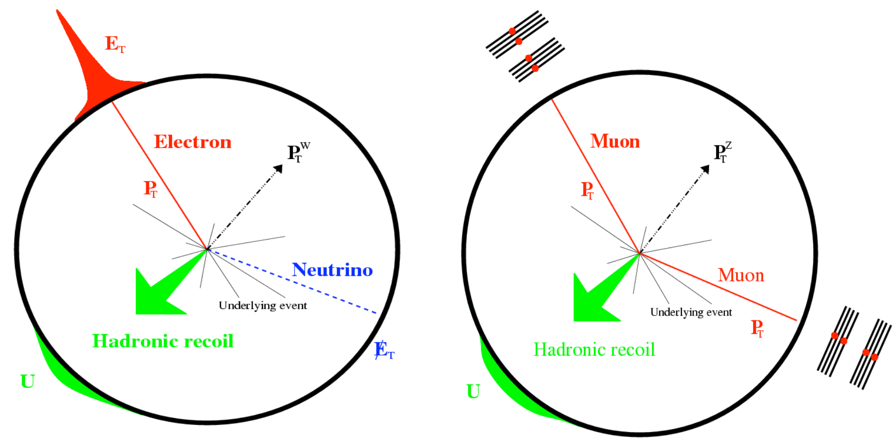


```
Run   152507
Event 1222318

DiJet Mass = 1364 GeV (corr)

z vertex   = -25 cm
```

W and Z Bosons

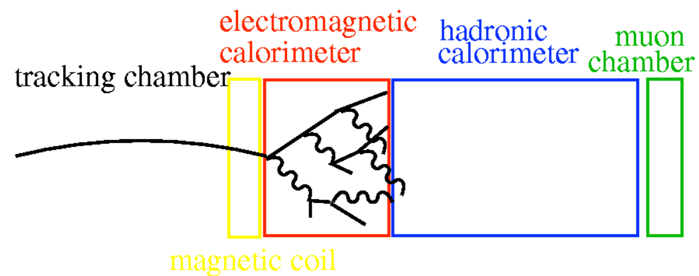
- Focus on leptonic decays:
  - Hadronic decays ~impossible due to enormous QCD dijet background
- Selection:
  - Z:
    - Two leptons E_T>20 GeV
      - Electron, muon, tau
  - W:
    - One lepton E_T>20 GeV
    - Large imbalance in transverse momentum
      - Missing E_T>20 GeV
      - Signature of undetected particle (neutrino)
- Excellent calibration signal for many purposes:
  - Electron energy scale
  - Track momentum scale
  - Lepton ID and trigger efficiencies
  - Missing E_T resolution
  - Luminosity …



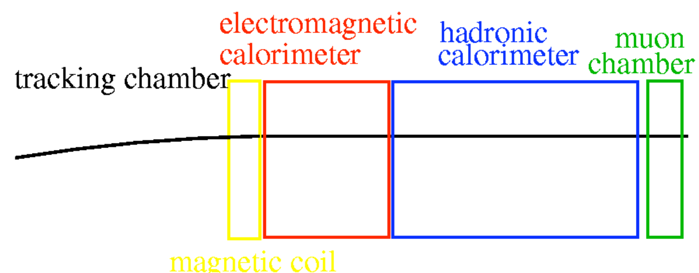


Lepton Identification

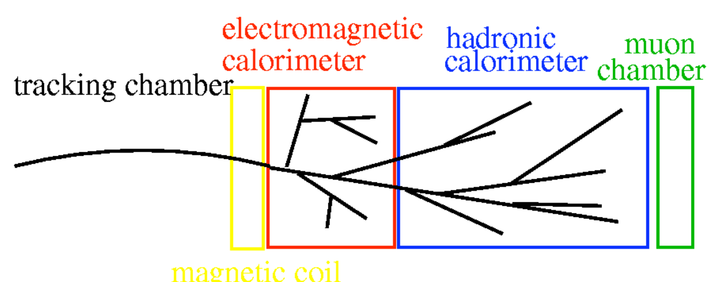
- Electrons:
  - compact electromagnetic cluster in calorimeter
  - Matched to track



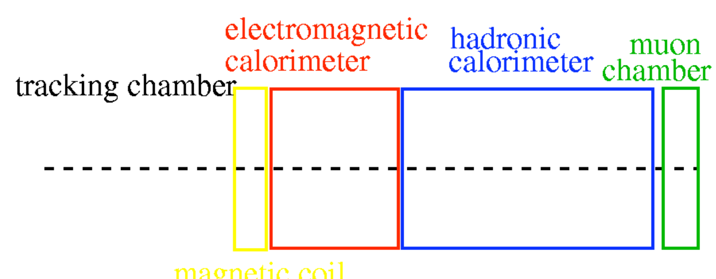
- Muons:
  - Track in the muon chambers
  - Matched to track



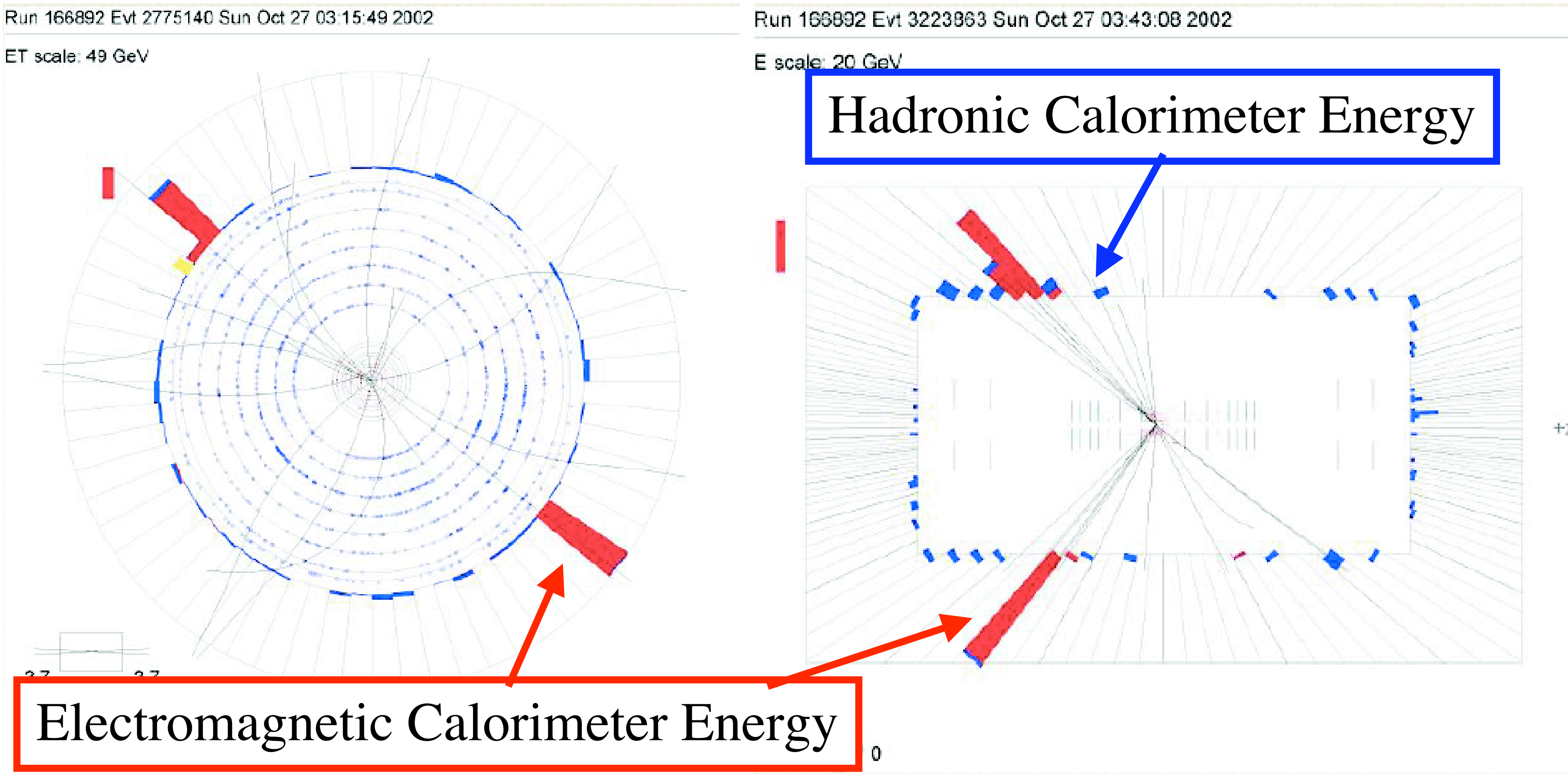
- Taus:
  - Narrow jet
  - Matched to one or three tracks



- Neutrinos:
  - Imbalance in transverse momentum
  - Inferred from total transverse energy measured in detector
  - More on this in Lecture 4



Electrons and Jets

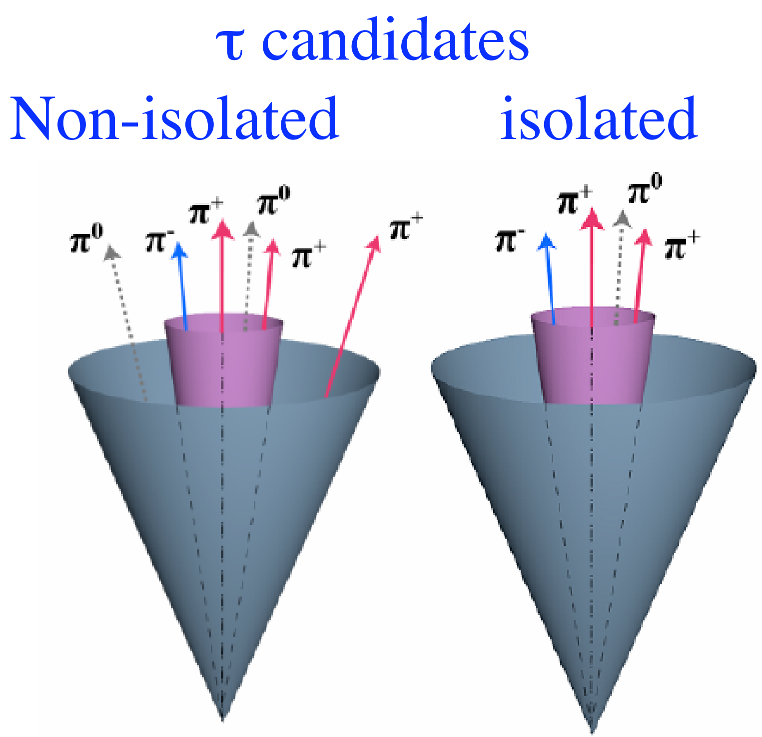


- Jets can look like electrons, e.g.:
  - photon conversions from π^0's: ~13% of photons convert (in CDF)
  - early showering charged pions
- And there are lots of jets!!!

The Isolation Cut

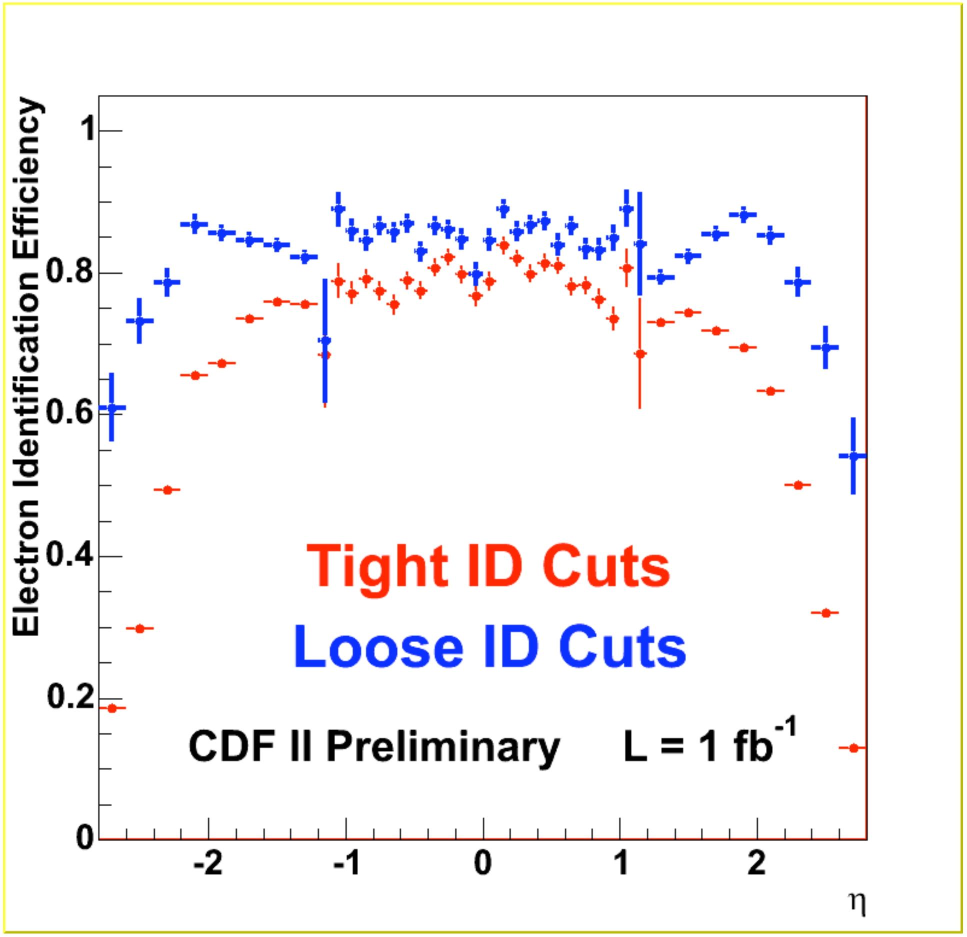
- Isolation is very powerful for isolated leptons
  - E.g. from W's, Z's
- Rejects background from leptons inside jets due to:
  - b-decays
  - photon conversions
  - pions/kaons that punch through or decay in flight
  - pions that shower only in EM calorimeter
- This is a physics cut!
  - Efficiency depends on physics process
    - The more jet activity the less efficient
    - Depends on luminosity
      - Extra interactions due to pileup

- Isolation cut:
  - Draw cone of size 0.4 around object
    - Sum up P_T of objects inside cone
    - Use calorimeter or tracks
  - Typical cuts:
    - <10% x E_T
    - <2-4 GeV



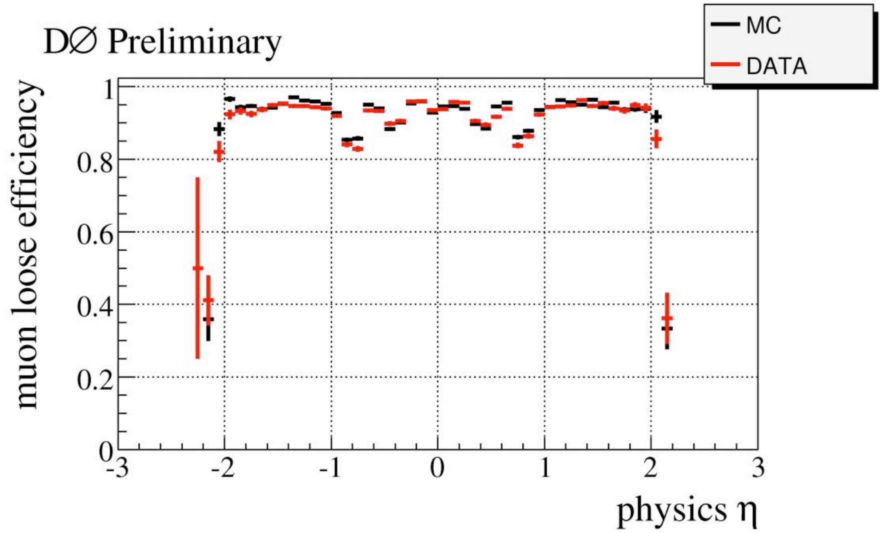
Electron Identification

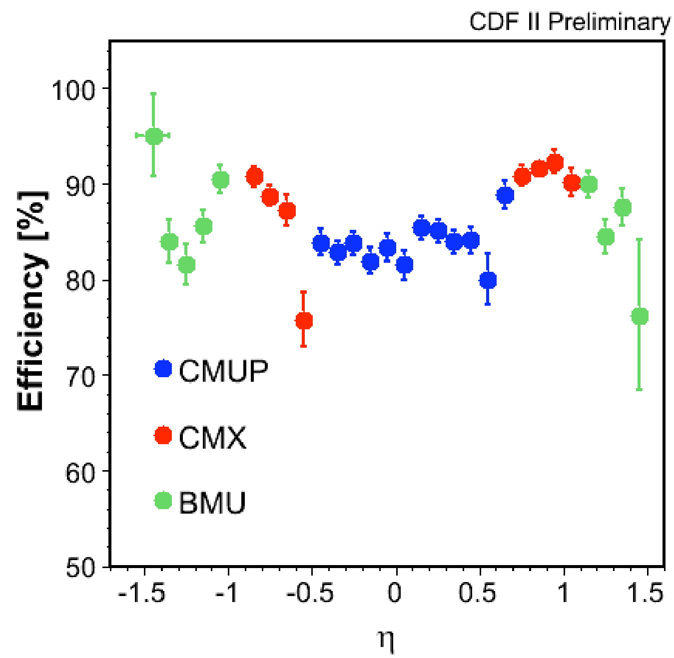
- Desire:
  - High efficiency for isolated electrons
  - Low misidentification of jets
- Cuts:
  - Shower shape
  - Low hadronic energy
  - Track requirement
  - Isolation
- Performance:
  - Efficiency:
    - Loose cuts: 86%
    - Tight cuts: 60-80%
    - Measured using Z's
  - Fall-off in forward region due to limited tracking efficiency



Muon Identification

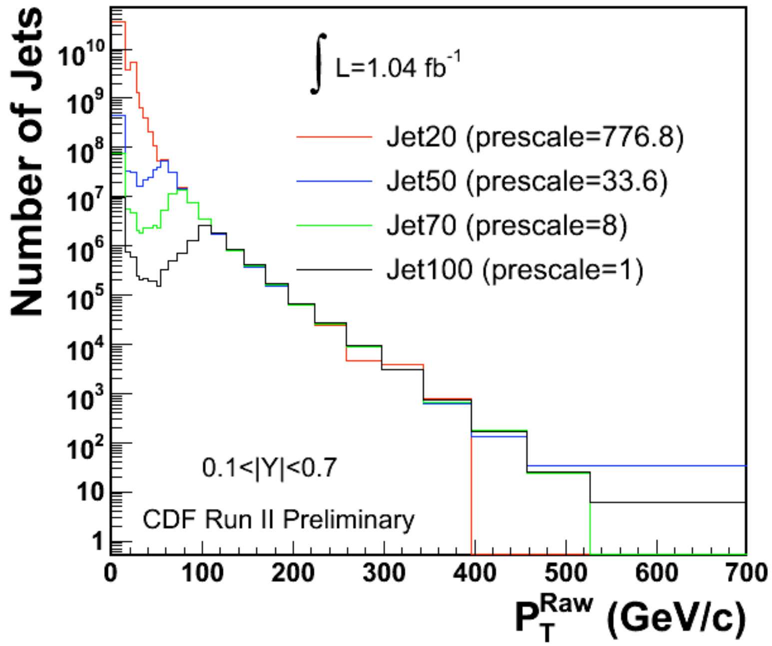
- Desire:
  - High efficiency for isolated muons
  - Rejection of background due to punch-through etc.
- Typical requirements:
  - Signal in muon chamber
  - Isolation
  - Low hadronic and electromagnetic energy
    - Consistent with MIP signal
- Efficiency 80-90%
- Coverage:
  - DØ: Up to |η|=2
  - CDF: up to |η|=1.5



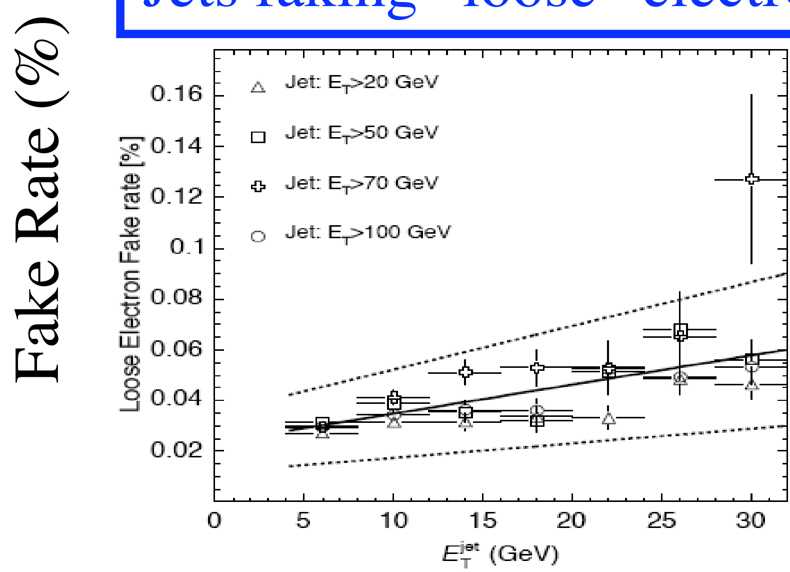


Jets faking Electrons

- Jets can pass electron ID cuts,
  - Mostly due to
    - early showering charged pions
    - Conversions: $\pi^0 \rightarrow \gamma\gamma \rightarrow ee+X$
    - Semileptonic b-decays
  - Difficult to model in MC
    - Hard fragmentation
    - Detailed simulation of calorimeter and tracking volume
- Measured in inclusive jet data at various E_T thresholds
  - Prompt electron content negligible:
    - N_{jet}~10 billion at 50 GeV!
  - Fake rate per jet:
    - Loose cuts: 5/10000
    - Tight cuts: 1/10000
  - Typical uncertainties 50%



Jets faking "loose" electrons

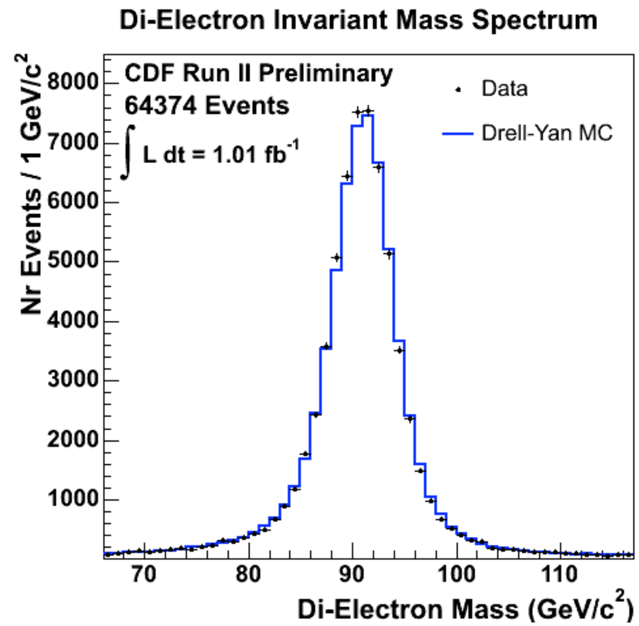


W's and Z's

- Z mass reconstruction
  - Invariant mass of two leptons

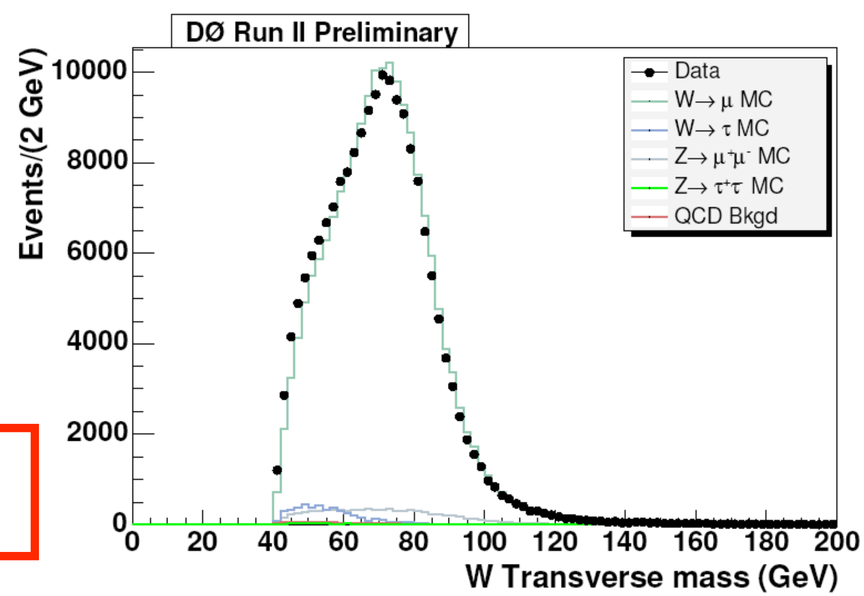
$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

  - Sets electron energy scale by comparison to LEP measured value



- W mass reconstruction
  - Do not know neutrino p_Z
  - No full mass resonstruction possible
  - Transverse mass:

$$m_T = \sqrt{|p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2}$$

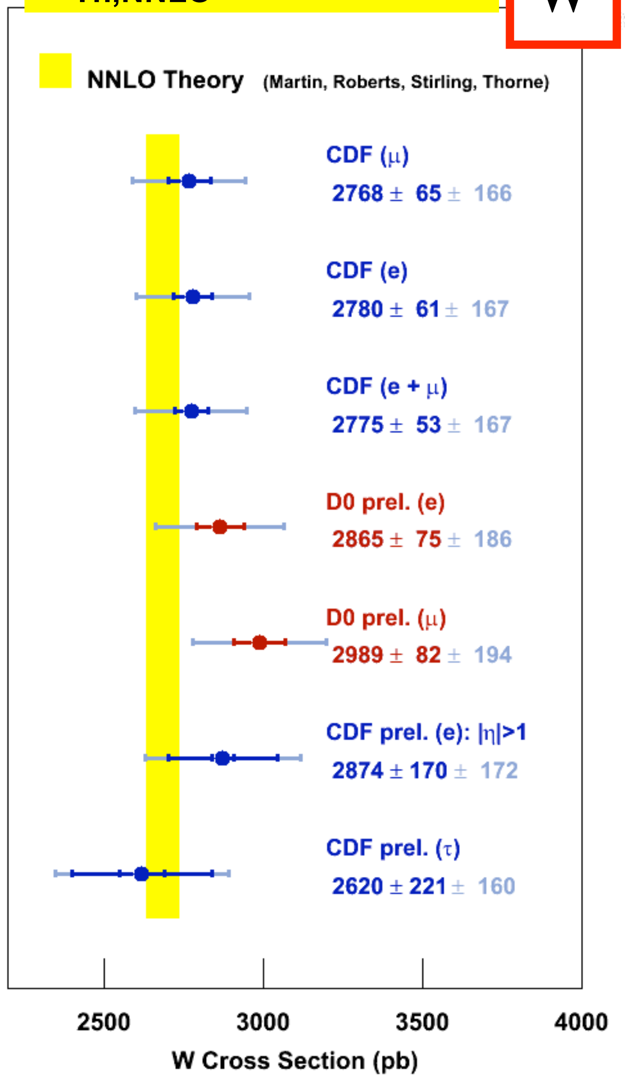


W and Z Cross Section Results

- Experimental And theoretical errors:
  - ~2%
- Luminosity uncertainty:
  - ~6%
- Can use these processes to normalize luminosity absolutely
  - Is theory reliable enough?

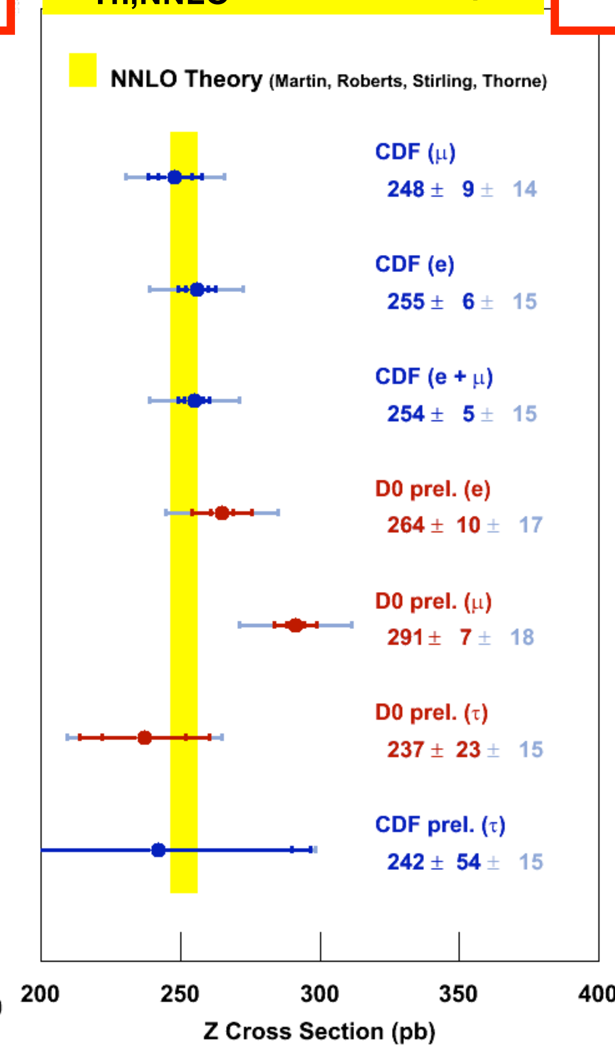
$\sigma_{Th,NNLO}$=2687±54pb

W

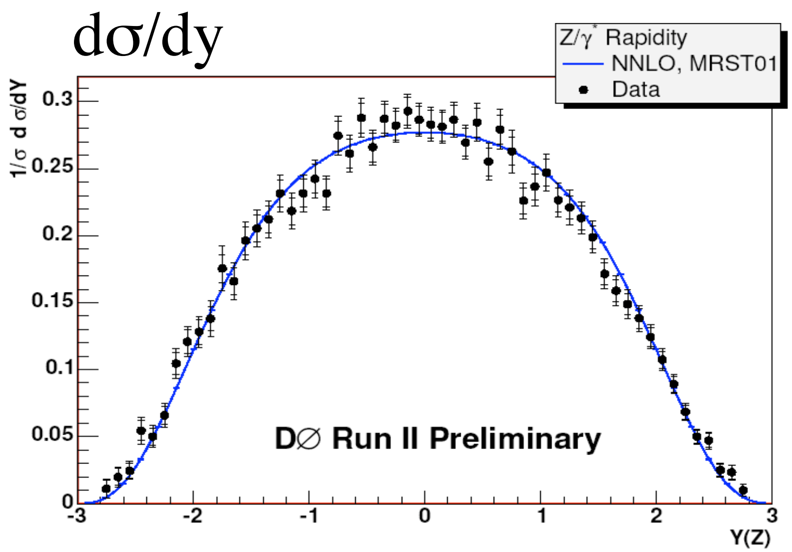


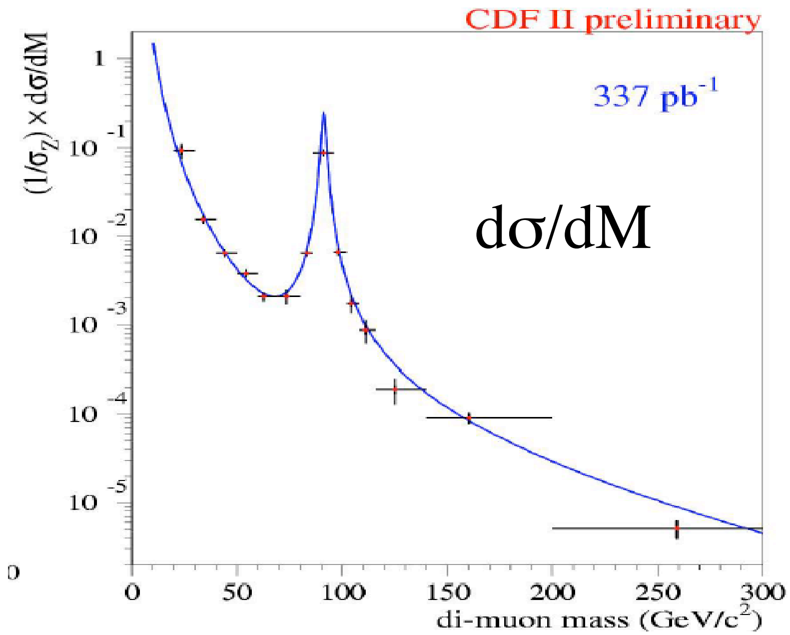
$\sigma_{Th,NNLO}$=251.3±5.0pb

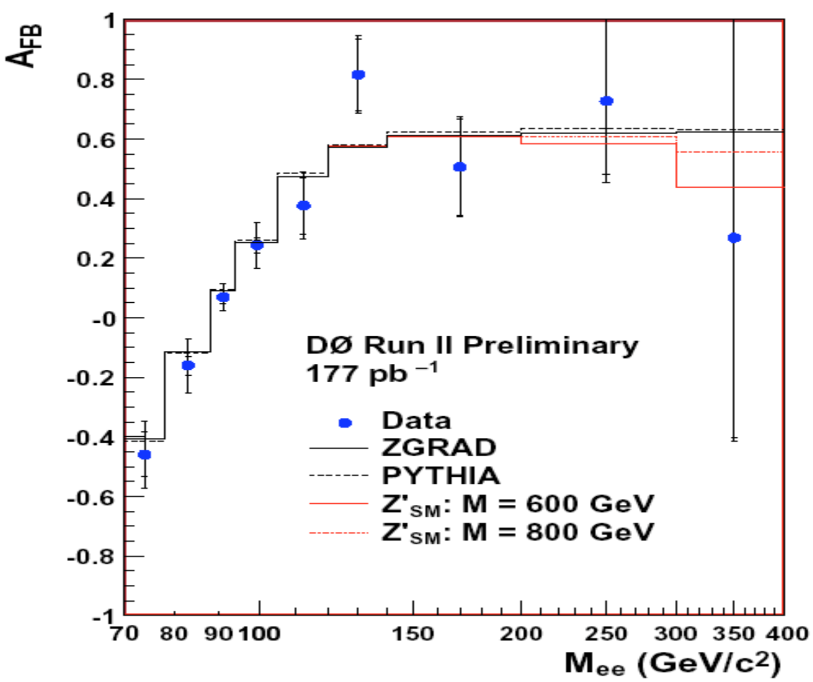
Z

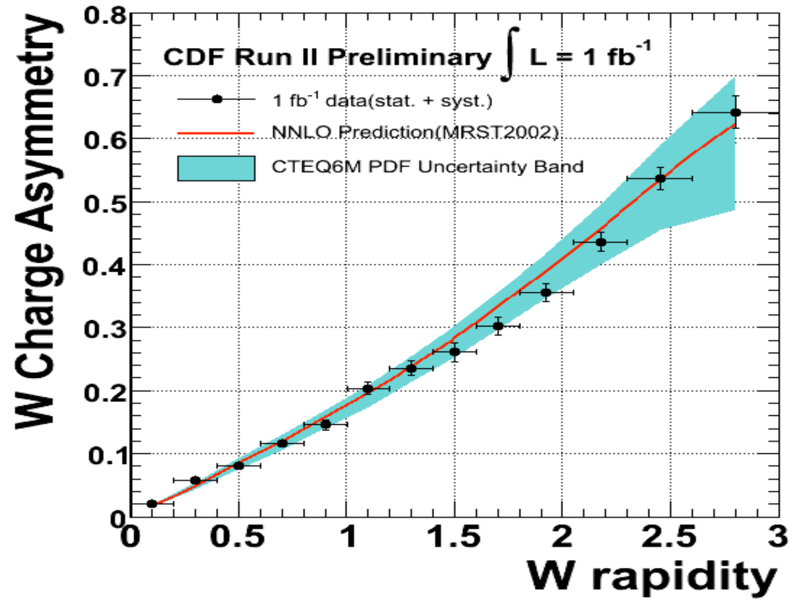


More Differential W/Z Measurements

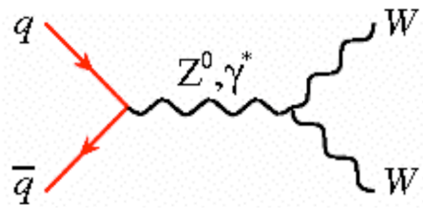


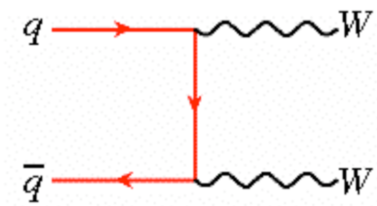


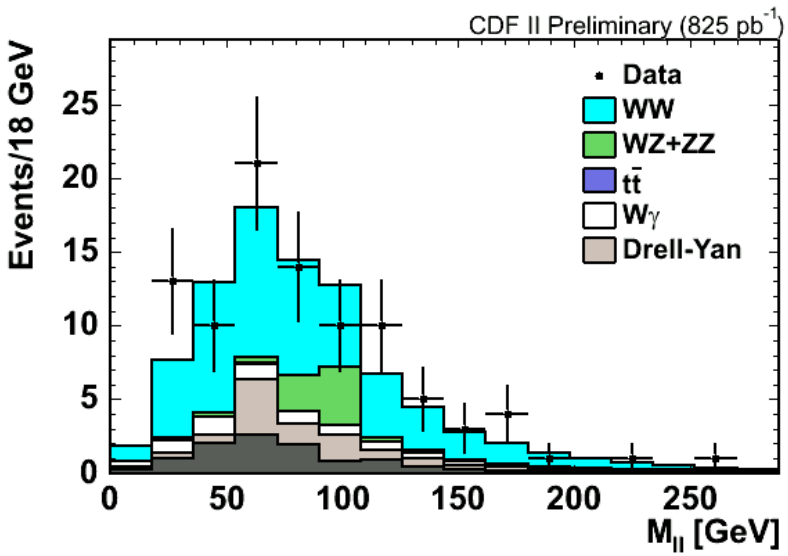




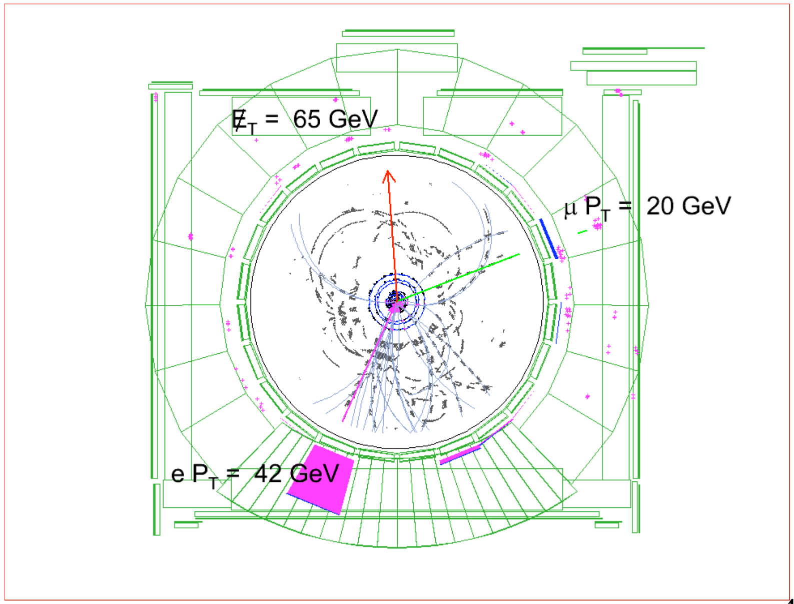
WW Cross Section



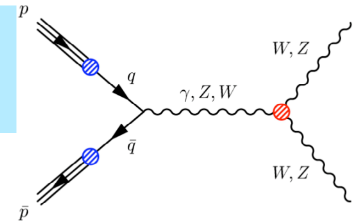


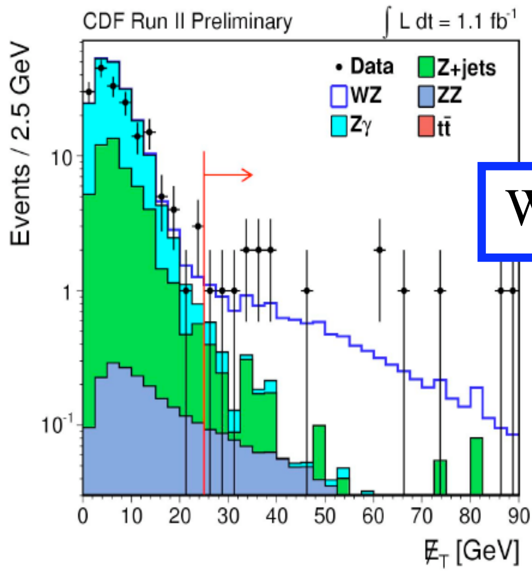


- WW cross section
  - Use $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$
  - 2 leptons and missing E_T
- Result:
  - Data: σ=13.6 ± 3.1 pb
  - Theory: σ=12.4 ± 0.8 pb
    - J. Campbell, K. Ellis (NLO)

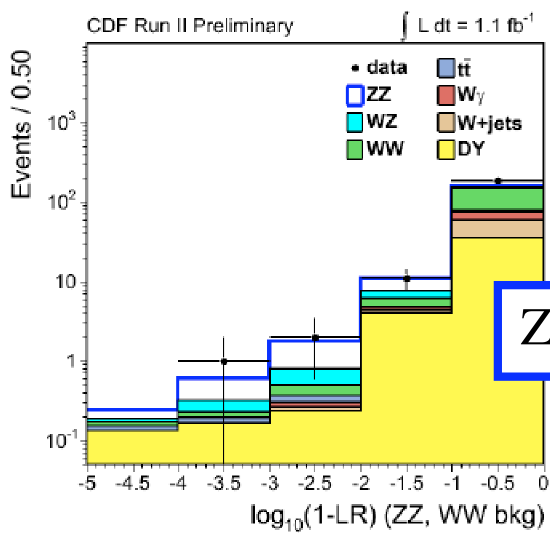


Diboson Production: WZ,ZZ





WZ→lllν



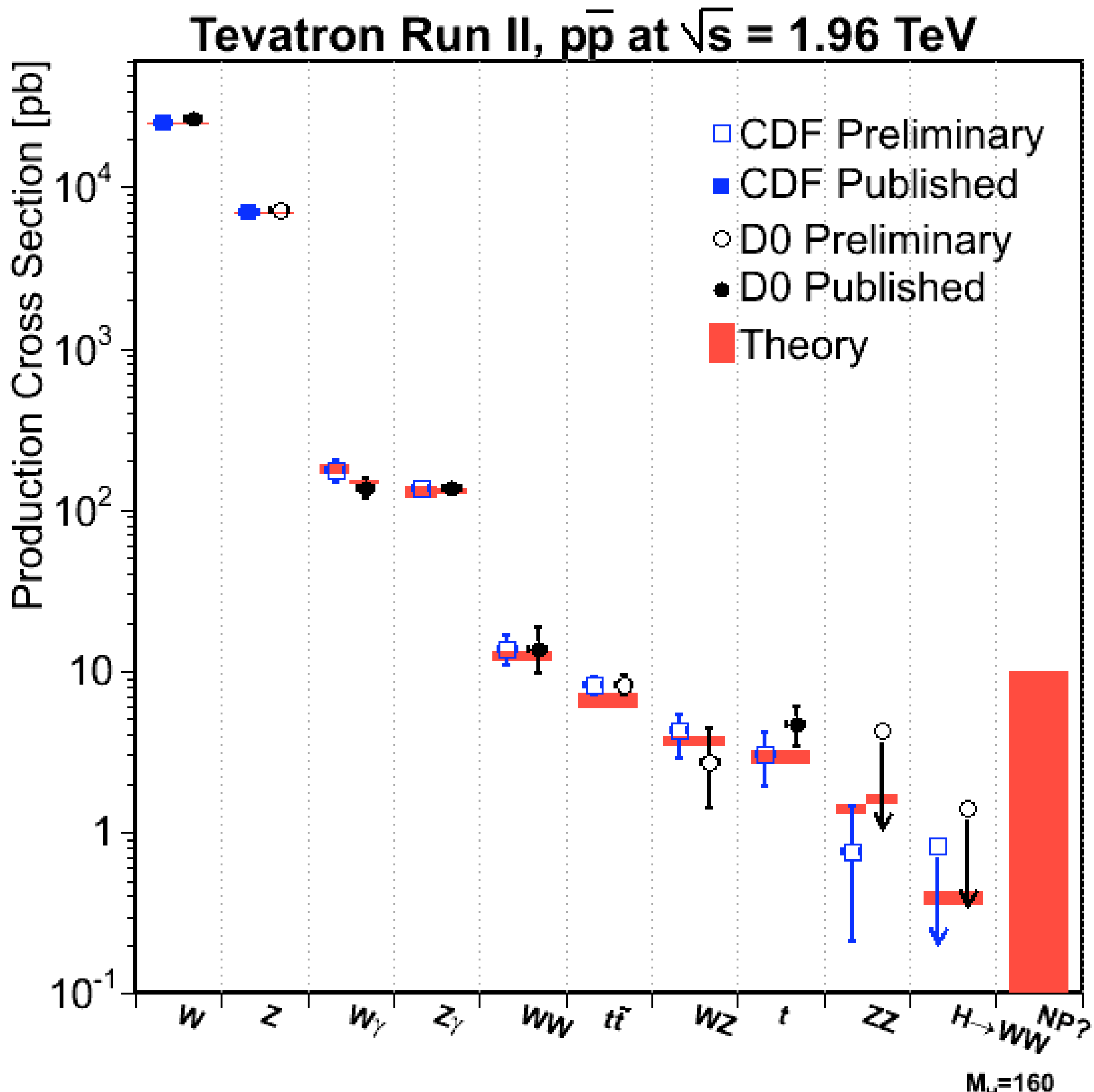
ZZ→llνν

- WZ:
  - 5.9σ observation
  - Cross section: $5.0^{+1.8}_{-1.6}$ pb
- ZZ:
  - 3.0σ evidence
    - llll mode: 2.2σ
    - llνν mode: 1.9σ

CDF DØ ZZ→llll

CDF	DØ	
2.51+-0.16	1.71+-0.11	ZZ expected
0.029+-0.021	0.17+-0.04	Bkg expected
1 (4μ)	1 (eeμμ)	Yield observed

Production Cross Section Summary



Higgs Boson and new physics are next in line!

Conclusion

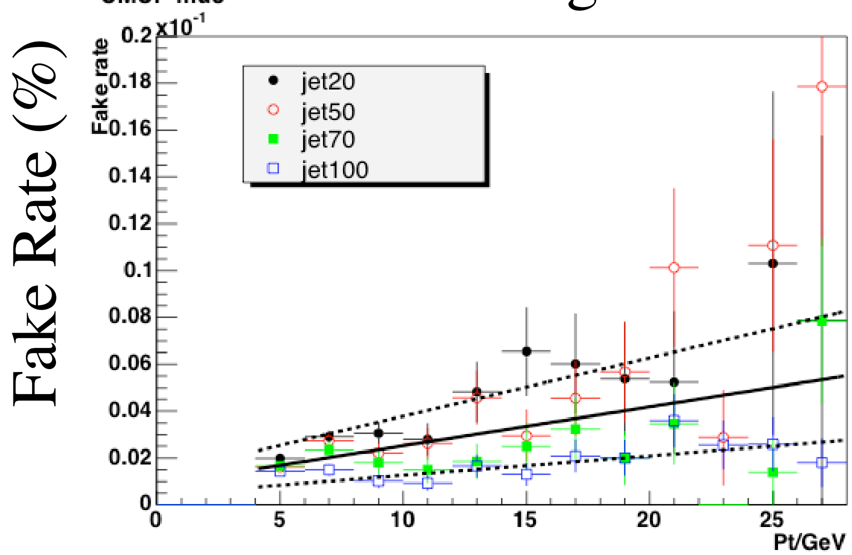
- Tevatron is world's highest energy collider today
  - Large datasets with $L=3\ fb^{-1}$ now available in Run II
    - 30 times more statistics than in Run I
  - CDF and DØ detectors operate well
    - Powerful tracking
    - Good calorimeter coverage
    - Good lepton identification
- A hadron machine provides a challenging environment
  - Cross sections of jets, W's and Z's and other processes at $\sqrt{s}=1.96$ TeV well understood
    - Excellent agreement with QCD calculations
    - This is important before moving on to rarer processes, precision measurements and new physics searches
      - See the next 3 lectures!

Backup Slides

Jets faking Muons

- Jets can pass muon ID cuts,
  - Mostly due to
    - Pions punching through
    - Pions or kaons decaying in flight:
      - $K^{\pm} \rightarrow \mu^{\pm}\nu$, $\pi^{\pm} \rightarrow \mu^{\pm}\nu$
    - Semileptonic b-decays
  - Difficult to model in MC
    - Hard fragmentation
    - Detailed simulation of calorimeter and tracking volume
- Measured in inclusive jet data at various E_T thresholds
  - Prompt muon content negligible
  - Fake rate per loosely isolated track:
    - Cannot measure per jet since isolated muon is usually not a jet!
    - 2/1000
  - Typical uncertainties 50%

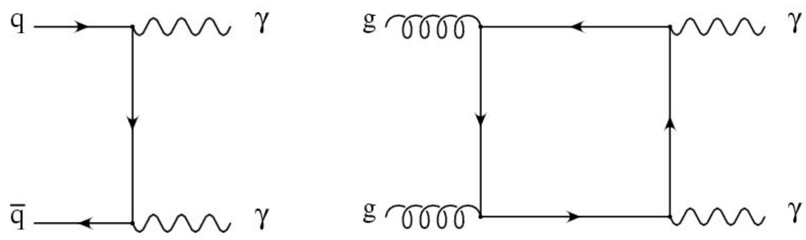
Tracks faking muons

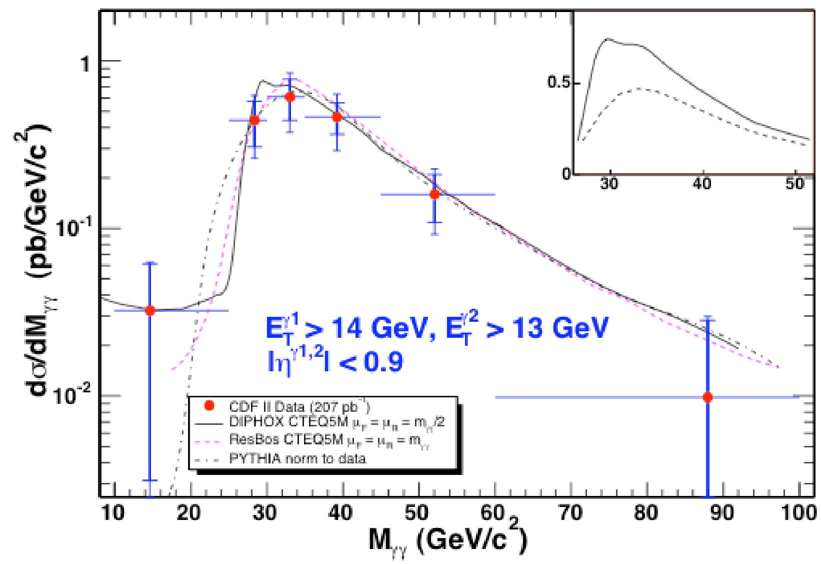


A Few Comments on Monte Carlo

- Critical for understanding the acceptance and the backgrounds
  - Speed: CDF ~10s per event, DØ ~ 3m per event
- Two important pieces:
  - Physics process simulation:
    - PYTHIA, HERWIG
      - Working horses but limitations at high jet multiplicity
    - “ME generators”: ALPGEN, MADGRAPH, SHERPA, COMPHEP,…
      - Better modeling at high number of jets
      - Some processes only available properly in dedicated MC programs
        - » e.g. Wγ or single top
    - NLO generators (MC@NLO)
      - Not widely used yet but often used for cross-checks
  - Detector simulation:
    - GEANT, fast parameterizations (e.g. GFLASH)
- Neither physics nor detector simulation can generally be trusted!

Diphoton Cross Section





- Select 2 photons with E_T>13 (14) GeV
- Statistical subtraction of background
  - mostly $\pi^0 \to \gamma\gamma$
- Data agree well with NLO
- PYTHIA describes shape
  - normalization off by factor two